PivotBuoy

An Advanced System for Cost-effective and Reliable Mooring, Connection, Installation & Operation of Floating Wind

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D5.5 Final performance assessment (operational regime and under extreme sea conditions) & model validation

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Document History

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31/03/2023	3.0	Comments from X1 on v2.0 integrated. No significant changes in conclusions.

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ACRONYMS

ADCP	Acoustic Doppler Current Profiler	**RNA**	Rotor nacelle adaptor
CFSR	Climate Forecast System Reanalysis	**SPM**	Single-point mooring
DTU	Technical University of Denmark	**TLP**	Tension leg platform
FOW	Floating offshore wind	**WP**	Work package
PLOCAN	Oceanic Platform of the Canary Islands		

EXECUTIVE SUMMARY

The final task in Work Package 5 is the evaluation of the X30 performance and the validation of the models in HAWC2 and OrcaFlex.

The HAWC2 and OrcaFlex models have been updated to reflect several small changes to the design during the manufacturing process. The floater frequencies of the coupled models have been compared in HAWC2 and OrcaFlex. The HAWC2 frequencies are significantly different (up to 16%) from the OrcaFlex frequencies due to unidentifiable modelling differences; however, this does not impact the validation results due to a previously unknown bug in the HAWC2 Morrison formulation discussed below.

Due to unforeseen delays in the commissioning of the turbine, there was no normal production data available for use in the validation work. This report focuses there on the validation of the floater frequencies and of a resonance phenomenon that was observed in simulation, which can be completed using currently available data. The validation of the platform during normal production will therefore be presented in the final report for the project.

The floater frequencies are validated using one-to-one simulations in HAWC2 and OrcaFlex using wind time series extracted from the data and wave spectral parameters from data and forecasts. Simulations using both a single swell and double swells are compared with the data. The OrcaFlex simulation with multiple swells is found to match the data extremely well. The pitch-heave and roll frequencies match the data almost exactly, indicating a high model fidelity. The HAWC2 results do not match well due to a previously unknown bug in the Morrison formulation, causing unexpected drift.

A resonance phenomenon observed in simulation was also investigated using data from a short pitch run-up test. The phenomenon was observed in the experiment but with a very low amplification factor, possibly due to increased damping or lower shear in the experimental conditions. The phenomenon is thus confirmed to be of a lesser concern in operation, though it will be continually monitored throughout its operation. A small resonance was unexpectedly seen in a rotor mode with 6P excitation, a phenomenon that was confirmed as being also present in land-based rotors when discussed with the manufacturer. The pitch run-up test thus indicates that the performance of the X30 platform is satisfactory in terms of potential resonance issues.

The objectives of this deliverable are fulfilled. The performance of the platform is validated using measurements, and the simulation results in OrcaFlex are very good. Significant learning was achieved in the consortium during the execution of tasks in this work package, which has led to improvements in the modelling of weathervaning single-point mooring concepts such as the PivotBuoy X30 and has highlighted key focus areas for similar tasks in future projects.

1   INTRODUCTION

To combat the effects of climate change that are already causing serious issues worldwide, society must transition to renewable energy sources. One such renewable energy source is floating offshore wind (FOW), where wind turbines are installed on floating platforms offshore, where the wind resource is greatest. However, the current technology readiness level is too low, and the price of energy too high, for the mass adoption of existing FOW systems.

The objective of the PivotBuoy project is thus to develop and validate an innovative floating system that will significantly reduce the cost of energy when adopted at scale. As part of the project, a prototype has been designed, manufactured and installed off the coast of the Oceanic Platform of the Canary Islands (PLOCAN) in Gran Canaria. The activities in Work Package 5 (WP5) have focused on the evaluation of the platform performance using aeroelastic simulation tools at different design phases, and in this final deliverable, the models are validated using data from the installed prototype.

The X30 prototype has been modelled in two different softwares: OrcaFlex, developed by Orcina [1], and HAWC2, developed by the Technical University of Denmark (DTU) [2]. HAWC2 was originally developed for onshore wind turbines and has been subsequently expanded to model floating turbines. OrcaFlex, on the other hand, was originally developed for modelling mooring lines of rigid floating systems. In 2018, it released its first wind turbine module, which has undergone some further evolutions in the past several years. The cross-comparison of these two softwares is thus of extreme relevance in the project: OrcaFlex is robust on modelling hydrodynamics, and HAWC2 has very advanced modelling of wind turbine dynamics.

It should be noted that the original description of project work stated that, in addition to HAWC2 and OrcaFlex, the X30 would also be modelled in OpenFAST, an aeroelastic software developed by the National Renewable Energy Laboratory [3]. However, OpenFAST fundamentally assumes a single tubular tower on a floating platform and thus cannot be used to model systems like the X30. The resources intended for the OpenFAST modelling efforts were therefore replaced by CFD simulations of 50-year extreme waves impacting the PivotTop, which were presented in Deliverable 5.2. The removal of cross-verification with OpenFAST is not expected to reduce the impact of the results in this work package, as the modelling methodology is quite similar to HAWC2.

Unfortunately, the validation presented in this report does not include any data in which the turbine is operating in normal production. This is due to unforeseen delays in the installation and commissioning of the turbine, and thus no production data is available at the time of writing. The validation efforts have thus focused on two fronts. The first is a validation of the floater frequencies with a one-to-one validation using data recorded on the X30 platform in a non-operational state. The second is the verification of a resonance problem that was predicted in OrcaFlex, using data from a pitch run-up test. Validation of the prototype with normal production is expected in the final project report, assuming the turbine and grid are soon deemed safe to operate in normal production.

Finally, the manufacturing phase resulted in some necessary changes to the design. Thus, the OrcaFlex and HAWC2 models needed to be updated and cross-checked with each other before the validation could occur. This report therefore summarizes the changes in the X30 specifications that have occurred since Deliverable 5.2, in addition to presenting the validation results.

The objectives of the report are as follows:

- Summarize the changes in the design since the publication of 5.2.
- Cross-verify the HAWC2 and OrcaFlex floater frequencies after updates from the manufacturing phase.
- Validate the floater frequencies using data from the X30 platform.
- Validate the presence of resonance phenomena using data from a pitch run-up test.

2   DESIGN OF THE X30

This section describes the general geometry of the X30 platform and summarizes design changes since the publication of D5.2.

2.1   X30 Platform Description

To properly understand the subsequent discussions of the platform behaviour, it is necessary to present a general overview of the X30 platform as well as the terminology used to refer to certain parts.

The X30 platform consists of a Vestas V29 rotor mounted in a downwind configuration upon a triangular substructure (see Figure 1). The platform has a single-point mooring (SPM) to a triangular tension-leg platform (TLP). Directly above the TLP platform is the Pivot Top, which contains the control room for the platform. Because of its direct connection with the TLP, the Pivot Top is extremely stable even in rough sea conditions. The mast connecting the Pivot Top to the nacelle is called the pivot mast. The two columns below the rotor are the main columns, and the symmetric masts connecting the nacelle to the main columns are the main masts. There are heave plates included in the design to improve hydrodynamic performance of the platform.
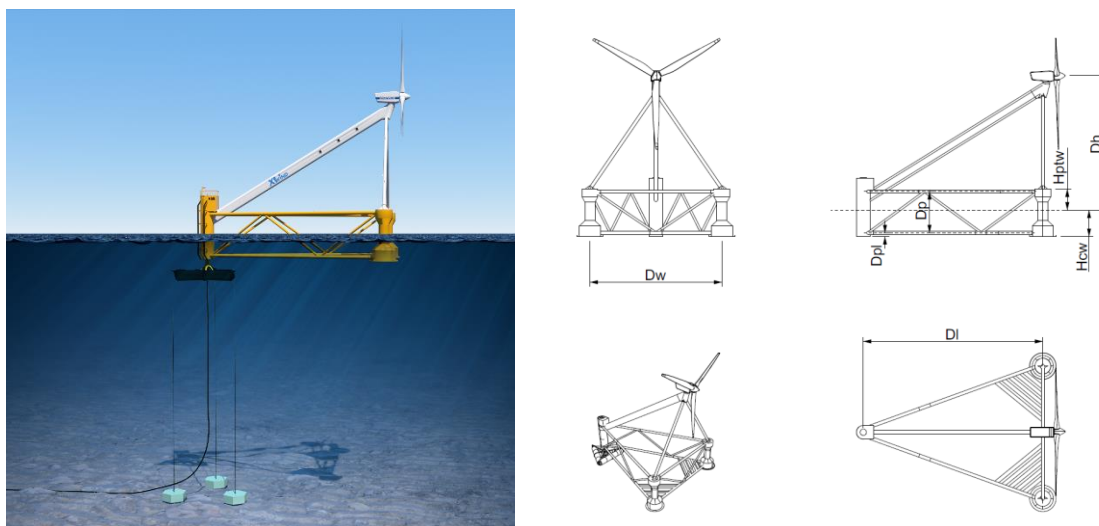

Figure 1: Rendering (left) and general layout (right) of the X30 floating system.

2.2   Updates in the design

Deliverable 5.2 "Simulation results for PLOCAN 1:3 part-scale prototype" presented analyses of the performance of the X30 platform at the PLOCAN site, simulated using both OrcaFlex and HAWC2. As noted above, there were changes in the design due to the manufacturing process. Thus, both the OrcaFlex and HAWC2 models needed to be updated before any cross-verification or validation could occur. The changes in the X30 include the following:

● Addition of a rotor-nacelle adaptor (RNA) and yaw flange
● Additional mass due to extra outfittings such as stairs, landing, electrical equipment, etc.
● Three added tanks–one to the PivotTop and one to each main column–to counter the extra weight and increase platform stability

- Modified hydrodynamics of heave plates based on CFD simulations
- Small updates in the pivot mast and main masts
- Various additional minor changes

A basic cross-verification of the two models was performed, which included a comparison of total platform mass, centre of gravity, and steady-state position. All values were found to be within 1%, except for the vertical position of the centre of mass, which was 0.6 m higher in HAWC2. The cause of the discrepancy is currently unknown, but it was decided that the value was small enough that it was not expected to significantly impact results.

The design changes due to the manufacturing process were not found to significantly impact the expected performance of the platform when evaluated using OrcaFlex.

3 CROSS-VERIFICATION OF FLOATER FREQUENCIES

After the basic cross-verification of the two models, a more detailed cross-verification was conducted by comparing the natural frequencies and mode shapes of the floating platform.

A complicated system such as the X30 platform includes many different natural frequencies in different frequency bands. Natural frequencies whose mode shapes are dominated by rigid-body motion of the platform are referred to as floater frequencies, and have the lowest frequency. When designing a floating system, these frequencies should either fall below the wave-energy spectrum (see Figure 2) or be heavily damped. At a higher frequency band occur the structural modes, which features significant deflection of the platform and/or rotor in the mode shape. Depending on the platform and rotor, these mode shapes can take very different forms and fall in different frequency bands. A diagram of the common sources of excitation and frequency bands is given in Figure 2.
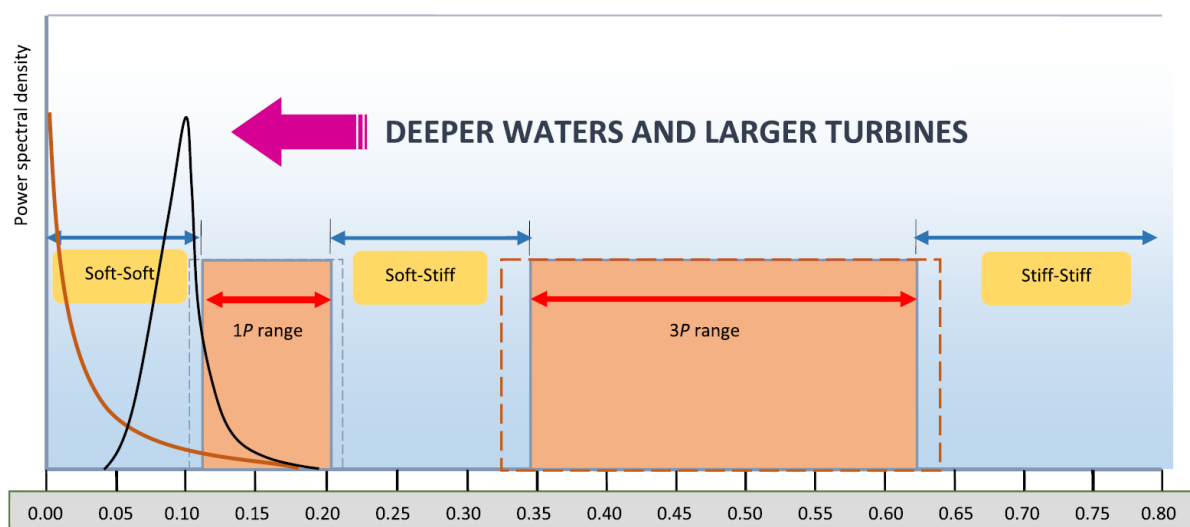

Figure 2: Excitation frequency bands. Atmospheric turbulence contains energy in very low-frequency bands, indicated by the orange line. Waves excite the system in the frequency band of around 0.05 to 0.2 Hz, depending on the site. The operation of a 3-bladed turbine results in forcing frequencies once per revolution (1P) and three times per revolution (3P). Because the turbine operates between a minimum and maximum rotor speed, this produces the light-orange bands in the plot. Platforms are generally designed such that lightly damped structural frequencies fall in one of the regions highlighted in yellow. Reprinted from [4].

For the cross-verification of the HAWC2 and OrcaFlex models, it was decided to focus on the floater frequencies of the system, as these were much more likely to be excited in the validation data with the ambient wind and wave conditions.

The floater frequencies were determined via different methods in the different softwares. In OrcaFlex, the floater frequencies and mode shapes can be outputted directly via an eigenanalysis that includes hydrodynamic forces. The eigenanalysis frequencies generated in OrcaFlex were compared to values extracted from free decays and found to match almost exactly. To get the floater frequencies in HAWC2, initial efforts utilized the "system eigenanalysis" option. This command calculates the natural frequencies and mode shapes of a floating system, but after extensive debugging and discussions with the developers it was realized that the command does not include added mass from the Morrison equations. This significantly impacted the roll, pitch-heave, surge, and sway frequencies. Thus, the HAWC2 floater frequencies were evaluated using a combination of free decays—for the roll, pitch-

heave, surge, and sway modes—and system eigenanalysis—for the TLP modes, which are not expected to be significantly impacted by Morrison forces.

The 6 floater frequencies of the platform are named based on the dominant motion of the platform for that mode: roll, surge, sway-roll, pitch-heave, TLP yaw, and TLP springing (see Figure 3). The roll mode is dominated by rotational motion of the platform around the x direction, where x is aligned with the wind. The platform surge mode is characterized by horizontal translation of the entire platform in the x direction. There is almost no pitch-heave motion in the surge mode. The sway mode is dominated by horizontal motion of the TLP perpendicular to the wind, in the y direction. The pitch-heave is dominated by vertical motion of the two main columns, resulting in a strong pitching motion for the nacelle. There is some motion of the TLP in the pitch-heave mode, but it is very small. The two TLP modes are dominated by motion of the TLP: the yaw mode by torsional motion and the springing mode by vertical motion. The mode shapes are diagrammed in Figure 3.
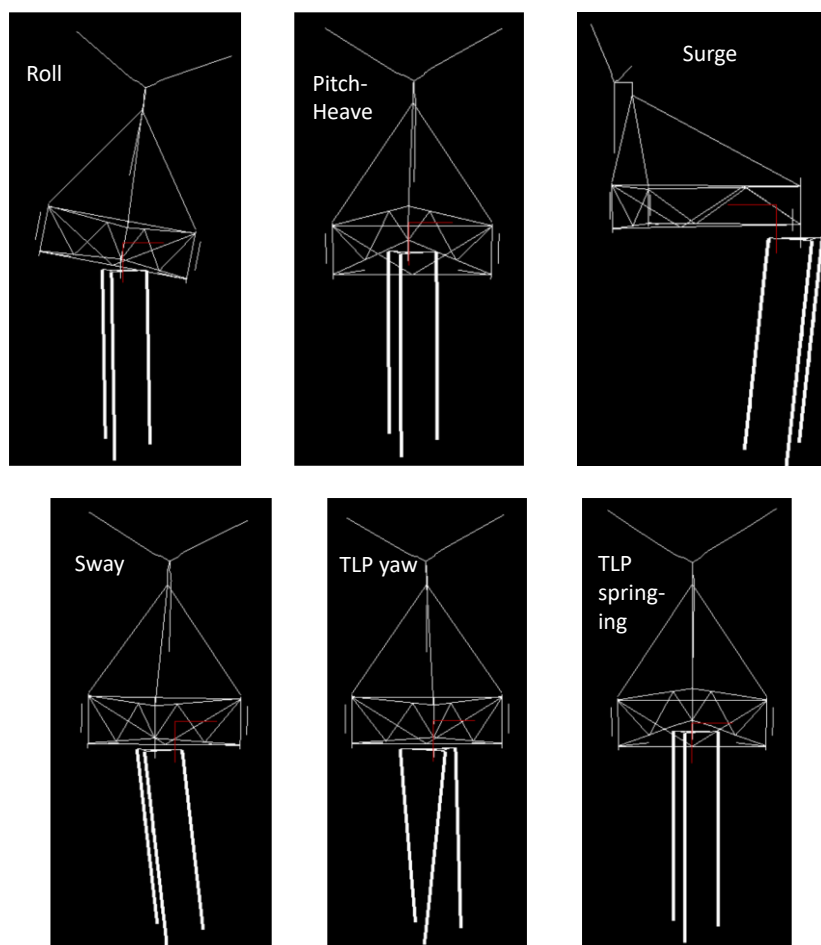

Figure 3: Mode shapes of floater frequencies. Top left: Roll. Motion dominated by out-of-phase vertical motion of the two main columns. Top middle: Pitch-Heave. Motion dominated by in-phase vertical motion of the two main columns. Top right: Surge. Motion dominated by lateral motion of the platform in the along-wind direction. Bottom left: Sway. Motion dominated by lateral motion of the PivotTop column. Bottom middle: TLP yaw. Motion dominated by torsion of the TLP. Bottom right: TLP springing. Motion dominated by vertical motion of the TLP. Note that the pitch-heave mode has almost no TLP motion, whereas the TLP springing mode has almost no main-column motion.

The floater frequencies for the OrcaFlex and HAWC2 models were determined with a standard ballast in the main columns of 3t and a tide of 0 m using the methods described above. The initial floater frequencies calculated using the HAWC model were significantly different from OrcaFlex: approximately 20% difference for the roll and heave-pitch frequencies, and approximately 10% difference for the surge and sway-roll frequencies. The discrepancies in the surge and sway frequencies were determined to be related to a too-high tension in the cables. The exact cause of the discrepancies in the roll and pitch-heave frequencies was unfortunately unable to be diagnosed due to a myriad of differences in modelling differences in the hydrodynamics of the two softwares. Ultimately, the buoyancy of the main columns and extra tanks was redistributed slightly (less than 5%) and the location of the towertop mass was moved slightly to reduce the discrepancy in the roll frequency. The final results after tuning are presented in Table 1 in normalized form.

Table 1: Normalized floater frequencies calculated using OrcaFlex eigenanalysis and HAWC2 free decays or system eigenanalysis (indicated by an asterisk).

	Roll	Pitch-Heave	Surge	Sway	TLP yaw*	TLP springing*
OrcaFlex	0.044 Hz	0.092 Hz	0.037 Hz	0.054 Hz	0.160 Hz	1.000 Hz
HAWC2	0.040 Hz (-10%)	0.106 Hz (+16%)	0.039 Hz (+4%)	0.057 Hz (+5%)	0.183 Hz (+14%)	0.883 (-12%)

Evan after tuning the parameters in the HAWC2 model, there are still significant differences between the OrcaFlex natural frequencies and the HAWC2 natural frequencies. We expect some differences in the TLP modes due to the neglecting of Morrison added mass in the system eigenanalysis, so it is possible that the difference in those modes is less than what is reported in the table. Regardless, the TLP modes are not considered in the validation analysis, so for the purposes of this report, differences in the TLP modes are not a significant issue. The differences in the other four modes, however, are not desirable and highlight the difficulty in cross-code verifications for complex platforms such as the X30. In the end, it was decided not to investigate the discrepancies in the HAWC2 model further, as significant resources had already been used to generate the results shown above. The remainder of the work was thus centred on the validation work, which is the true metric for whether these results are accurate.

4 PLOCAN SITE CONDITIONS

A detailed description of the installation site can be found in D4.1 [5]. The most relevant aspects of the site conditions are summarized here for convenience of the reader.

The X30 platform is installed off the eastern coast of Gran Canaria, a few kilometres away from the PLOCAN. PLOCAN is jointly driven by the Spanish and Canary Island governments to support research, development, and innovation of marine/maritime technologies. The PLOCAN facility is on the northeast coast of Gran Canaria, and the nearby 23-km^2 test site encompasses publicly owned sea and land off the coast. The water depth in the test site ranges from under 30 m to over 600 m (Figure 4), offering significant flexibility for technologies under development. The X30 installation location is approximately 1 km from the coast, at a water depth near 50 m.
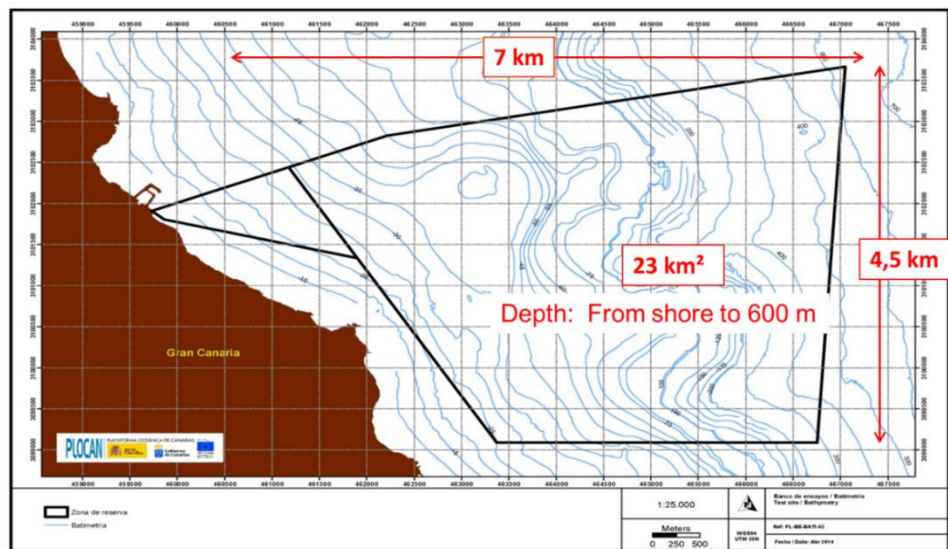

Figure 4. PLOCAN test site.

The wave roses near the X30 installation site—determined from the Las Palmas East wave buoy and SWAN numerical modelling [6]—are shown in Figure 5. The predominant wave direction is from the north-northeast direction. The predominant wave direction shows relatively little annual variation. The most common wave condition is a significant wave height of 1.5 m and a wave period of 8 seconds.
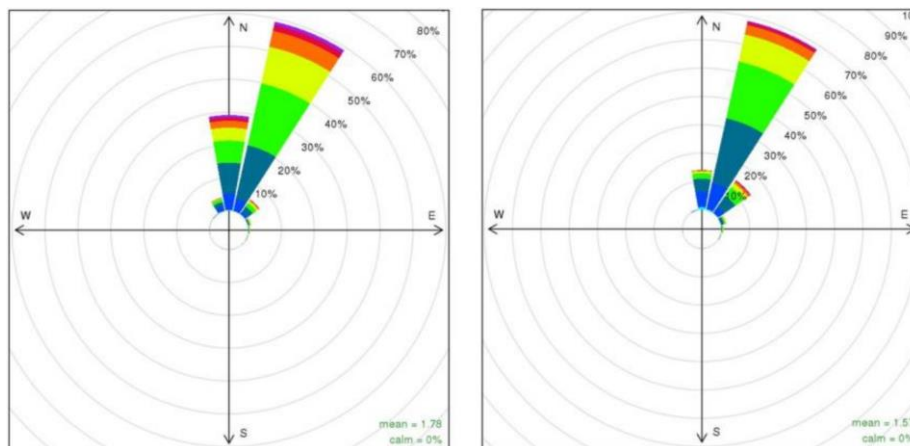

Figure 5: Wave rose at buoys near to installation site, calculated with SWAN numerical modelling [6].

The wind climate data is taken from the Climate Forecast System Reanalysis (CFSR) global modelling at a height of 10 m. The wind-speed data at this height can be converted to the relevant hub height of 25 m by multiplying by 1.047, assuming the 0.05 power-law exponent given in Table 2 of [5]. The annual profile, mean wind direction, and wind rose are presented in Figure 6 and Figure 7. The currents at the surface are primarily towards the south-southwest direction and have measured values that typically vary between 0 and 0.5 m/s [5].
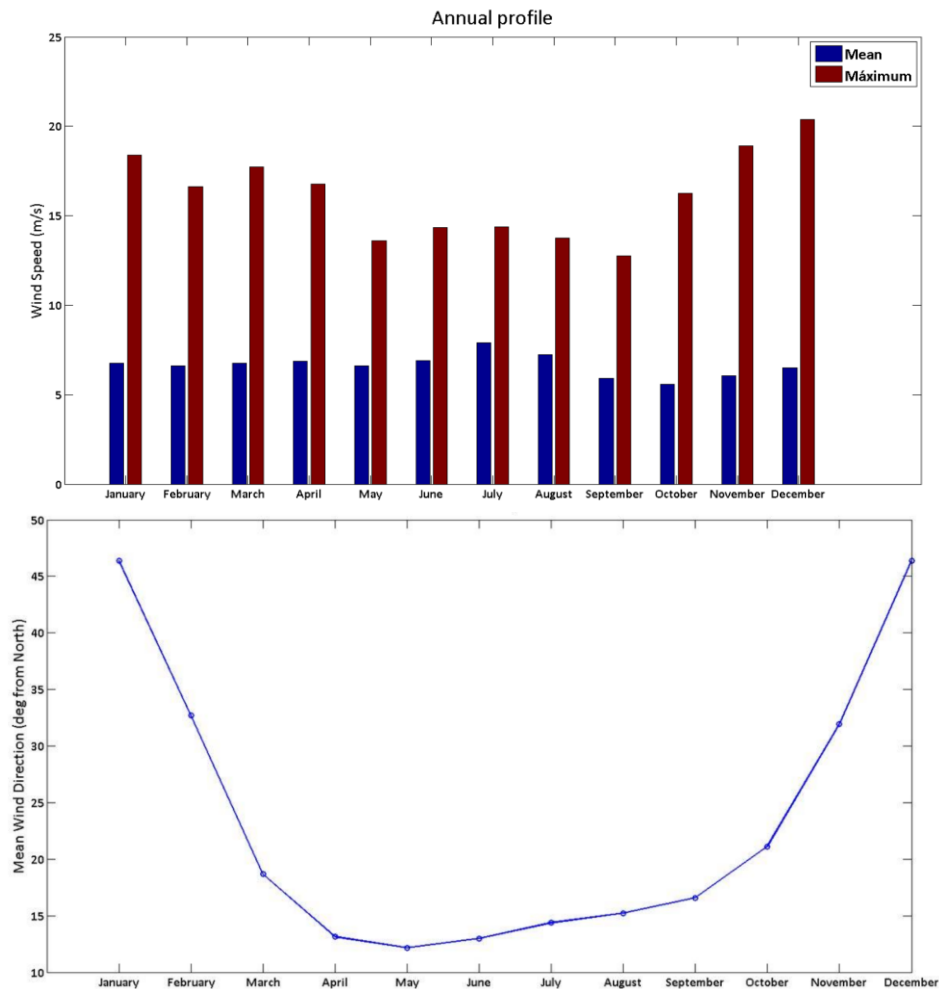

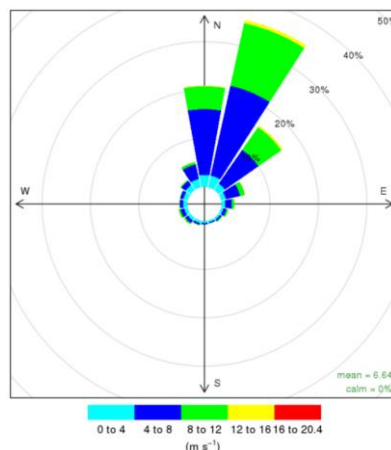Figure 6: Annual mean/max wind speeds (top) and mean direction (bottom).

Figure 7: Wind rose at installation site.

5 PLATFORM PERFORMANCE AND MODEL VALIDATION

This section presents the model validation using the available data from the X30 prototype.

5.1 Available data from platform

Due to unforeseen delays in the installation procedure, the platform was installed at the site in October of 2022 but was unable to be commissioned until February of 2023. Thus, the performance evaluation and model validation in this deliverable is performed using data in which the turbine is not operating. A small ramp-up test was conducted in February, in which the turbine was slowly spun up to an operating RPM. Normal production data and validation is expected in the final report.

The platform is equipped with a variety of sensors in the control room (Pivot Top), the pivot mast, and the main columns, in addition to the standard sensors that are installed in a V29 nacelle. The vibrations in the pivot mast are measured using both strain gages and a three-dimensional accelerometer. The motions of the pivot mast, main columns, and nacelle are also measured using accelerometers. The V29 nacelle inertial measurement unit (IMU) includes pitch, roll, and yaw, although the yaw measurement is not usable due to the platform motion. Most of the accelerometers except for the one installed in the control room have a bandwidth that begins at 1 Hz and are therefore not suitable for investigations into floater frequencies. Unfortunately, the sensor to measure the tension in the TLP cables was non-functioning, and thus there is no information on the cable forces. The wind speed is measured using the nacelle anemometer, and the direction can be inferred via the nacelle vane combined with the platform's yaw orientation.

In addition to the sensors on the platform, there are measurements of the wave conditions from nearby sources. A buoy installed 50 m away from the platform reports the significant wave height, max wave height, significant wave period, and wave direction every 30 minutes. Because secondary swells are often very closely aligned with the primary swells in the installation bay, the buoy cannot always properly identify secondary swells. The presence of secondary swells can thus be verified using forecasts from websites such as windguru.cz. The current measurements are extracted from a current model produced by the Puertos del Estado, the port system of Spain.

It should be noted that in addition to the measurement sources listed above, an Acoustic Doppler Current Profiler (ADCP) is installed on the sea floor below the platform. An ADCP device allows very accurate measurements of current and wave height spectra, which will reduce the uncertainty in the future validation with the production data. The data on the device is not accessible in real time, and thus the device must be recovered and the data extracted and post-processed before it can be used. The device has only been very recently recovered, and thus the metocean data is not available for use in this report.

5.2 Validation of floater frequencies

Because there is no normal production data, the primary focus of the validation efforts is on the floater frequencies. A one-to-one validation is therefore presented using 1 hour of data from the morning of January 22, 2023. The following subsections present the ambient conditions during the measurement acquisition, simulations with a single wave swell, and finally simulations with a secondary swell.

5.2.1 Ambient conditions

At that time, the wind was coming from the north-east direction, the current was directed towards the northwest, and the primary swell was also coming in from the north-east. The turbine was pitched to feather and passively floating. The wave and tidal conditions are summarized in the tables below.

Table 2: Metocean data (primary swell) for January 22, 2023.

	Hm_0	H_{max}	T_p	T_m	Wave direction
9:00 am	1.96 m	3.37 m	7.12 s	5.72 s	32.03°
9:30 am	1.93 m	2.84 m	7.45 s	5.67 s	39.59°
10:00 am	1.88 m	2.89 m	7.45 s	5.72 s	29.82°

Table 3: Tidal values at X30 installation site for January 22, 2023.

	9:00 am	9:10 am	9:20 am	9:30 am	9:40 am	9:50 am	10:00 am
Difference in MWL	-1.27 m	-1.25 m	-1.22 m	-1.18 m	-1.13 m	-1.08 m	-1.01 m

In addition to the primary swell recorded by the Las Palmas East wave buoy, a secondary swell was also forecasted 0° from north with a significant wave height of 1.1 m and a period of 11 s. A detailed discussion on this secondary swell is presented in Sec. 5.2.3. The current during that time was small: 4 cm/s from a direction of 286° from north. The tidal values during the measurement window are indicated in Table 3.

The wind speed and wind direction taken from the nacelle measurement unit. The wind comes from a north-easterly direction, but shifts more towards an east-northeasterly direction over the course of the measurement period. The mean wind speed of the anemometer data is 7.6 m/s and the mean direction is 70 degrees from north. A diagram of the platform orientation with the directions of wind, current, and wave swells is given in Figure 8.
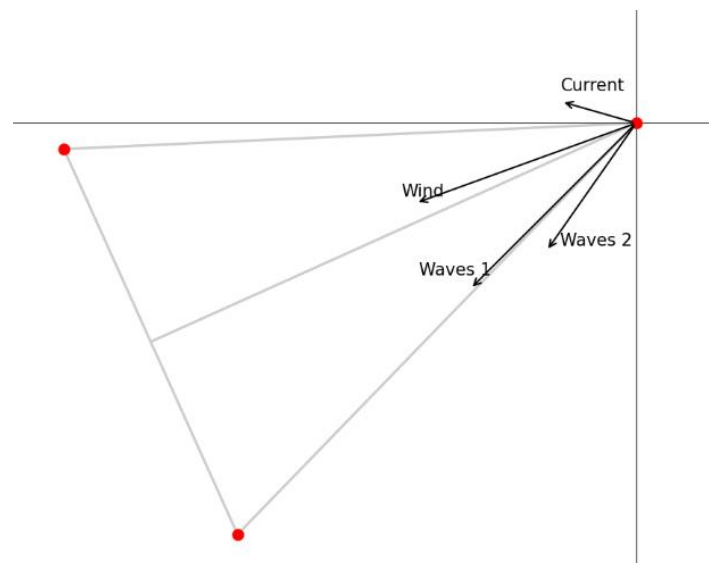

Figure 8: Diagram of mean wind, wave, and current direction.

5.2.2   Simulations with a single swell

In the beginning of the validation, the presence of the secondary swell was not considered, and therefore the initial simulations included only a single swell. These simulations with a single swell yielded a lot of insight into the behaviour of the platform and the impact of certain simulation parameters on the results, and thus the results are presented and analysed here. Only OrcaFlex results are presented here with the data, as the HAWC2 model was still undergoing the tuning of the floater frequencies described above. The HAWC2 validation is thus presented in Sec. 5.2.3 with the secondary-swell results from OrcaFlex.

The simulation settings for the wind and hydrodynamic parameters are shown in Table 4. The wind speed in the longitudinal and lateral directions were extracted directly from the dataset to maximize fidelity of the results. Current was included but not found to significantly impact the simulation results.

Table 4: Wind and wave simulation settings for one-to-one validation with a single wave swell.

Parameter	Value
Simulation length	3600 s
Ballast	4.5t in each main column
Wind speed	Extracted from data, 7.6, m/s average
Direction	Extracted from data, 70º N average
Tide	-1 m
Current	4 cm/s, 286º N
Wave type	Irregular, JONSWAP spectrum
Primary swell Hs and Tp	35º N, 1.93 m, 7.45 s

A time series and spectral visualization of the platform pitch signal for the OrcaFlex and data in both the time and frequency domain is shown in Figure 9. The comparison in the time domain shows an offset in the pitch signal for the OrcaFlex simulation that gradually reduces over the course of the simulation. This offset results from the tide, which changes over the course of the hour and causes a shift in the pitch signal as the main columns move up or down. It is only possible in OrcaFlex to simulate a tide that is constant over a simulation, so in the subsequent simulations with secondary swell, the tide parameter was updated to reflect the tide at the 30-minute mark instead of at the end of the measurement window.
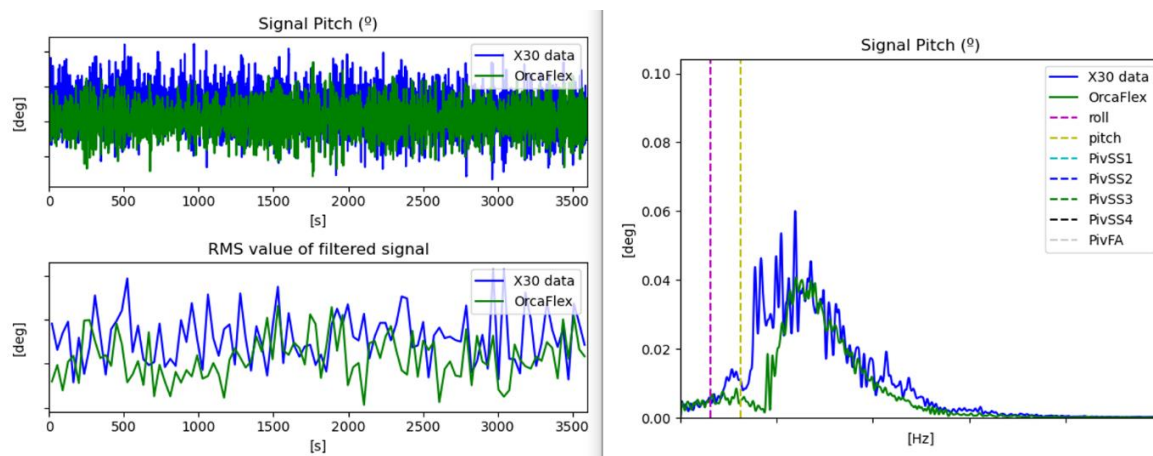

Figure 9: Comparison of pitch signal for data and OrcaFlex in the time domain (left) and frequency domain (right). The vertical lines indicate the floater frequencies from the eigenanalysis.

The bottom left plot analyses the root-mean-square (RMS) of the filtered pitch signal to consider if OrcaFlex is capturing any localized energy concentrations in the time domain. In general, the RMS of the OrcaFlex simulation is less than that of the data from the X30. This is primarily due to the unexpected presence of a secondary swell, which is discussed in more detail in the second paragraph.

The right plot in Figure 9 visualizes the same data as the left but in the frequency domain. All frequency-domain plots in this report are calculated by taking the fast Fourier transform (FFT) of the time series and then doubly filtering the result—once forward, once backwards—using a Butterworth filter to reduce noise.

The energy in the frequency band from approximately 0.1 Hz to 0.3 Hz is caused by wave excitation. It is immediately apparent that the wave energy in the OrcaFlex simulation matches the data well from 0.12 Hz onwards. However, the data indicates significant wave energy content in the region from 0.07 to 0.12 Hz that is not reflected in the OrcaFlex simulation. This indicates that the presence of a secondary swell with a lower frequency band that is not captured by the wave settings in this simulation.

Finally, the plot also indicates the excitation in the pitch signal caused by the pitch mode of the floater, which is visible in the data near 0.06 Hz. The OrcaFlex results do not show the same excitation of the pitch mode, which could be either due to the lack of wave energy in that frequency or due to hydrodynamic parameters of the heave plates that have too much damping. This is discussed further in Sec 5.2.3.
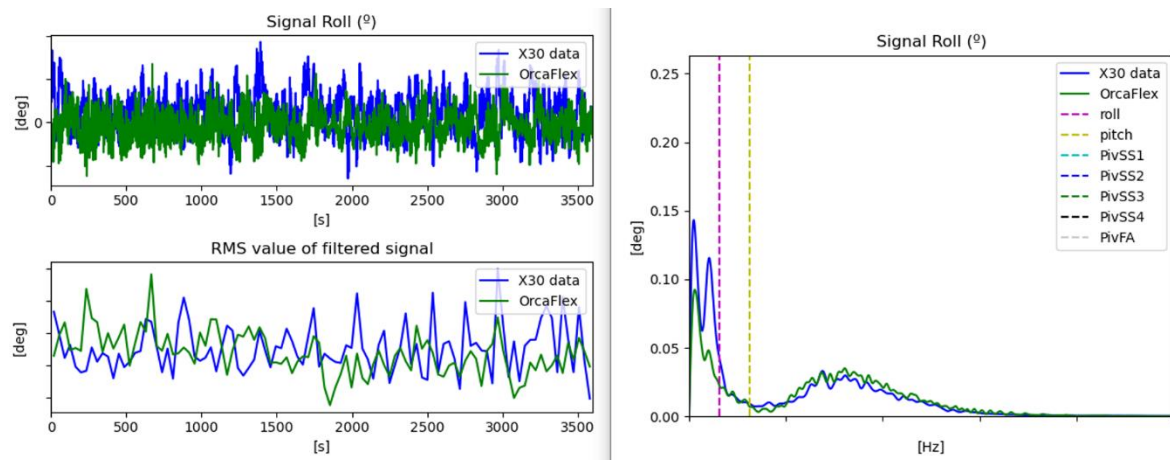

Figure 10: Comparison of the roll signal for data and OrcaFlex in the time domain (left) and frequency domain (right). The vertical lines indicate the floater frequencies from the eigenanalysis.

The comparison of the platform roll is given in Figure 10. The energy in the wave spectral band matches very well. Unlike the platform pitch signal, there are two peaks at very low frequencies that have a significant amount of energy. The energy in this band is caused by the wind, which excites at very low frequencies, and because the wind is not perfectly aligned with the platform at all times, it excites the platform in the roll direction. The peak near the vertical purple line is the roll natural frequency of the floater, and the peak in the OrcaFlex simulation matches the peak in the data almost exactly. There is an offset between the roll frequency in the data/simulations and the value predicted by the eigenanalysis. This is due to the presence of waves, which change the hydrodynamic forces on the platform and increase the added mass, thereby reducing the natural frequency. The lowest-energy

mode is possibly a lateral sway mode of the coupled system, and is visible in both OrcaFlex and the data. Note that there is an excellent match between the locations of the peaks in the data and the OrcaFlex simulation.

5.2.3   Simulations with a secondary swell

Based on the findings of the simulations with the primary swell, it was decided to tune and simulate a secondary swell in OrcaFlex. The forecast indicated a secondary swell originating from the north, thus, it was expected that the swell would be attenuated/rotated due to the shape of the island and the position of the X30 platform in an easterly facing bay. After several discussions and simulations, it was decided that the primary swell at the platform was coming in at 45° from north and the secondary swell was impacting the prototype at an angle 35° from north and attenuated to 0.8 m due to the island. The tide parameter was also updated to reflect the value midway through the measurement period instead of the value at the end based on the findings from the pitch signal in the single-swell simulation. A summary of the simulation parameters is given in Table 5.

Table 5: Simulation parameters for validation with secondary swell.

Parameter	Value
Simulation length	3600 s
Ballast	4.5t in each main column
Wind speed, direction	Extracted from data
Tide	-1.18 m
Current	None
Wave type	Irregular, JONSWAP spectrum
Primary swell ϑ, Hs and Tp	45° N, 1.93 m, 7.45 s
Secondary swell ϑ,Hs and Tp*	35° N, 0.8 m, 11 s

The HAWC2 model was also used to simulate the response of the platform for the one-to-one validation. However, HAWC2 only allows irregular waves with a single swell; thus, only the primary swell was included in the simulation.

A comparison of the wind speed, wind direction, and platform yaw angle for the data, the OrcaFlex simulation, and the HAWC2 simulations are given in Figure 11. There is a near-perfect agreement in the wind speed and direction in the two simulations, which is as expected because the wind series is extracted from the data.

The platform yaw position is quite different for the OrcaFlex and HAWC2 models. In particular, the HAWC2 yaw does not match the data particularly well. After significant efforts debugging the model and conversations with the developers, it was ultimately determined that there is a bug in the Morrison hydrodynamics calculations that causes a small lateral force to be exerted on the main columns. This small force is non-negligible when the turbine is not operating, and causes an offset in the yaw of the platform. As the wind speed increases and the drag forces on the rotor increase, the misalignment decreases. It is interesting to note that this issue is highlighted specifically because the analysis is for non-production data. If the turbine were operational, the thrust force would be significantly larger than the erroneous hydrodynamic force, and thus the yaw misalignment would not be noticeable.

Counter to the HAWC2 results, the OrcaFlex yaw results match extremely well considering the lack of detailed CFD simulations of the platform. The signal tracks the general trends of the data quite well, including small variations. There is a small tendency for the OrcaFlex simulation to overshoot the data, indicating that the damping of the yaw motion in the model is less than in simulation. Possible reasons for this include the model's lack of friction in the yaw bearing or small differences in the hydrodynamic parameters. Future work will investigate and potentially tune the hydrodynamic damping of the main columns, pontoons, and/or braces to reduce the overshoot of the yaw signal compared to data. However, the match between the OrcaFlex and data is already very satisfactory, supporting the hypothesis that the model accurately captures the relevant dynamics of the X30 prototype.
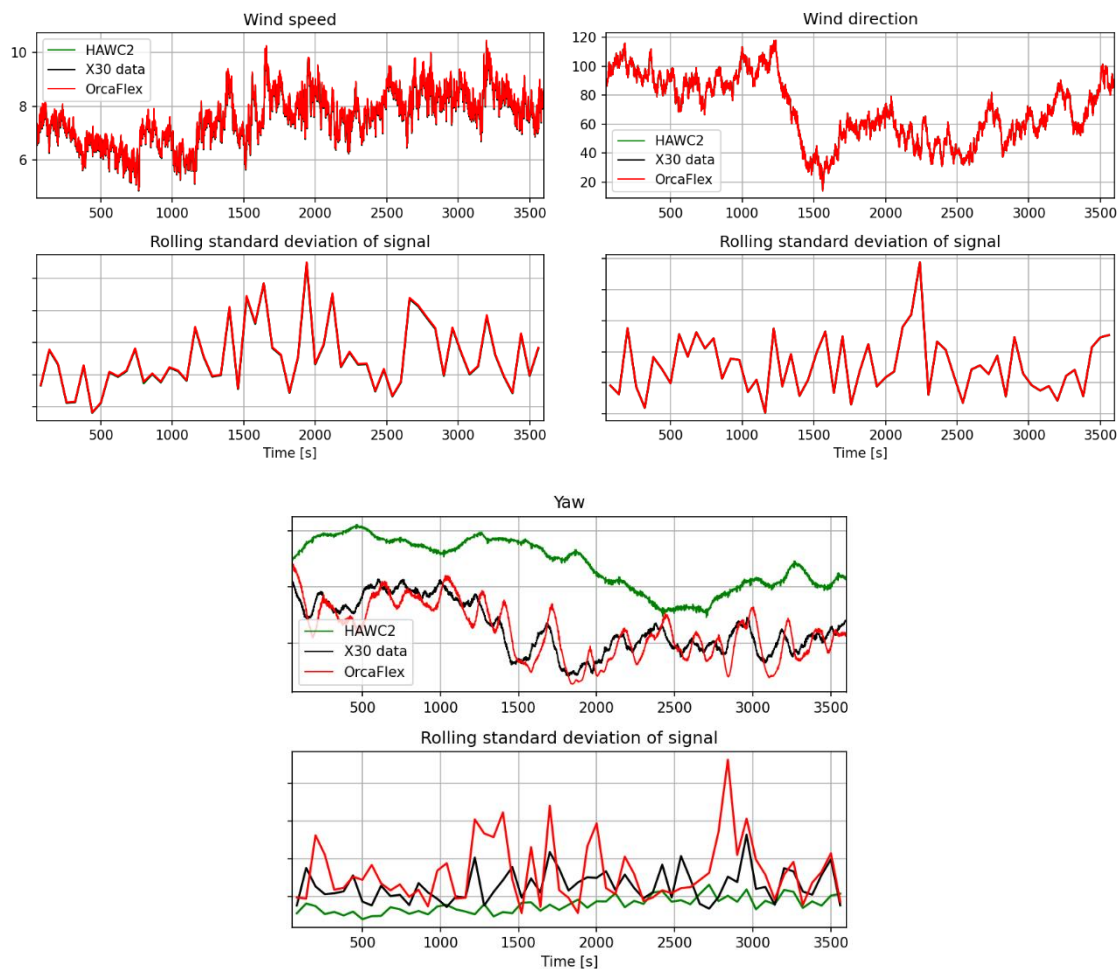

Figure 11: Comparison of wind speed, wind direction, and platform yaw for data, OrcaFlex simulation with secondary swell, and HAWC2 simulation with a single swell.

A comparison of the pitch signal is shown in Figure 12. In general, the match between the data and OrcaFlex simulation is once again extremely good both in the time and frequency domains, while the HAWC2 simulation is less accurate. The mean value of the pitch signal for the OrcaFlex model is now closer than the results in Sec. 5.2.2 due to the adjustment of the tide parameter. The mean value of the HAWC2 pitch signal is less than the OrcaFlex and the data, possibly because the buoyancy in the braces are not modelled.

The standard deviations of the data and OrcaFlex simulation are very similar, indicated by the bottom left plot and the area under the lines in the frequency domain. They are not expected to match exactly, as there was no data for the wave time series, and thus the waves are simulated randomly. The HAWC2 pitch is missing significant energy in the frequency domain, especially at the larger end of the wave spectrum. The reason is not clear at this time, but it is likely linked to the afore-mentioned bug in the Morrison calculations.

Comparing the results in Figure 12 versus Figure 9, it is clear that adding the secondary swell has increased the fidelity of the OrcaFlex results and successfully accounted for the missing energy. Interestingly, the pitch-heave mode is not particularly visible in the OrcaFlex simulation, although it is visible in the HAWC2 results and the data, distinguishable as a small peak in the spectrum near the vertical line. There could therefore be some fine-tuning of the hydrodynamics of the heave plates to reduce the damping of that mode, which would make it more visible in simulation.
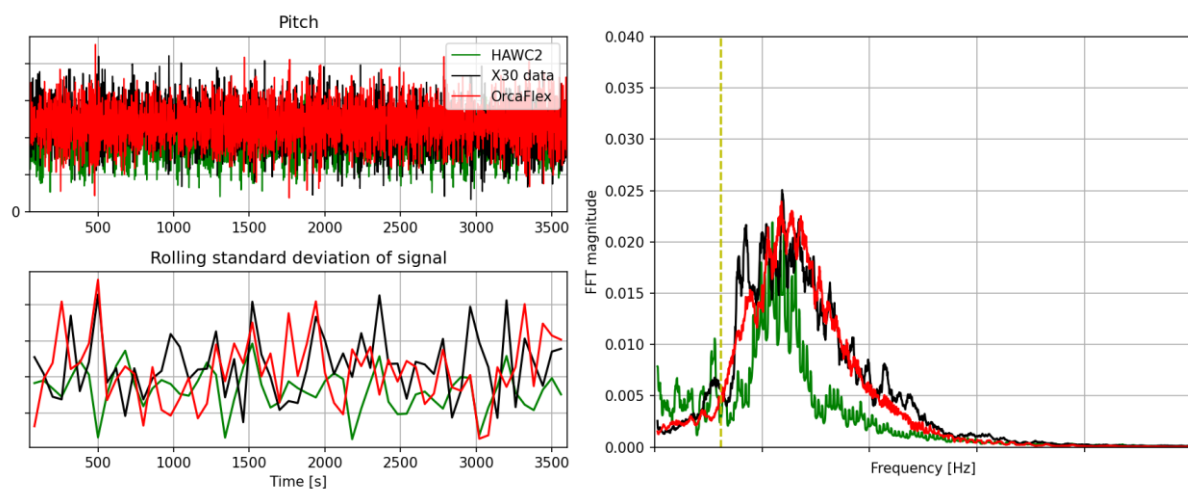

Figure 12: Comparison of the pitch signal for data, OrcaFlex, and HAWC2 in the time domain (left) and frequency domain (right) with a secondary swell. The vertical lines indicate the floater frequencies from the eigenanalysis.

The comparison of the roll signal is given in Figure 13. The HAWC2 roll is, as expected, quite different from the OrcaFlex simulation and data due to the reasons discussed above. The OrcaFlex simulation, once again, matches the data quite well. The impact of the secondary swell on the OrcaFlex roll signal is relatively small, because the swell is closely aligned with the primary swell direction and the platform, so there is little change in the OrcaFlex roll signal compared to the single-swell simulations. The wave spectral energy in the roll data matches OrcaFlex quite well.

In the time domain, there is a drift in the energy of the signal, indicated by the lines in the bottom left plot. This is visible in the top left plot by the difference in peak amplitude of the black and red lines. The cause of this drift in signal energy is hypothesized to be due to a small increase in the current that was not reported in the hourly data. An increase in the current would increase the hydrodynamic damping of the floater, causing it to react more slowly to changes in the wind speed. This would result in increased peak loading due to wind gusts, imparting more energy to the roll signal in the X30 prototype than what is seen in simulation. The impacts of current in the simulation performance are a subject of future work. It should be noted, however, that this sensitivity of the simulations to the current is only visible because the turbine is not operating. If it were, the thrust forces on the rotor would increase the platform alignment substantially, far outweighing changing currents. Thus, it is

expected that the analysis of the platform performance during production does not have the differences highlighted and discussed here.
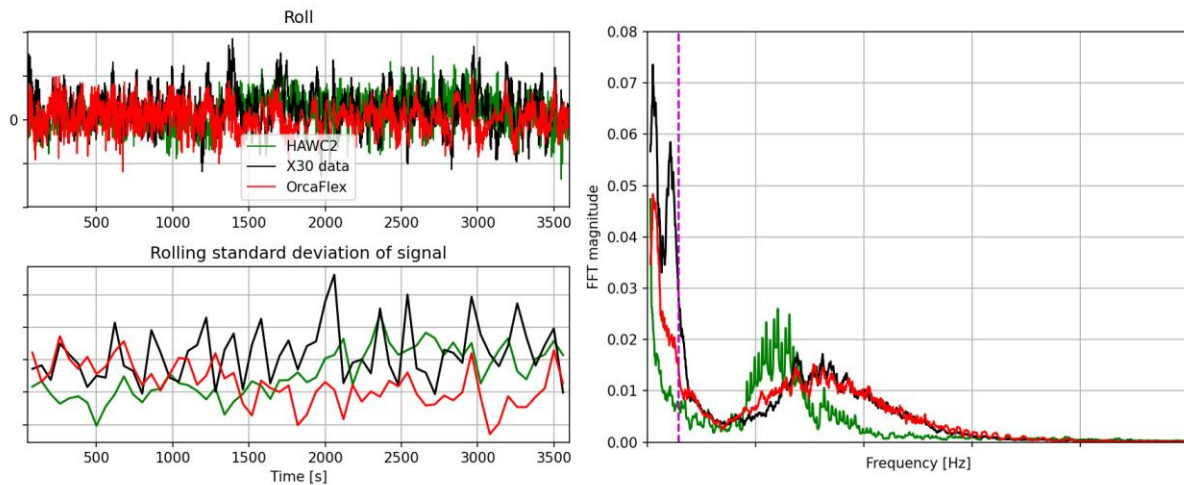

Figure 13: Comparison of the roll signal for data and OrcaFlex in the time domain (left) and frequency domain (right) with a secondary swell. The vertical lines indicate the floater frequencies from the eigenanalysis.

In summary, the comparisons of the HAWC2 simulations do not match the data particularly well. This is hypothesized to be caused by a bug in the Morrison implementation, which causes unexpected lateral forces on the main columns and results in platform drift for non-operating simulations. The OrcaFlex simulations indicate a high degree of fidelity in the model, lending weight to previous conclusions and simulations made with the platform. There are some areas to investigate still, in particular the effect of current on the hydrodynamic damping in the non-operating case. However, this effect is expected to be negligible during turbine operation. The model validation is thus adequately accurate to conclude that the objective of validating the model for a non-operating case is achieved.

5.3   Structural frequencies

In addition to the data acquired when the platform is passively operating, there is also a small run-up test that was conducted in early March as an initial demonstration of the platform. Results from run-up tests are extremely useful to verify whether any resonance phenomena predicted in simulation manifest in the physical system.

A comparison of the pitch test run-up with an OrcaFlex model of the pre-manufacturing X30 design is shown in Figure 14. Although the OrcaFlex model does not contain the changes summarized in Sec. 2.2, the changes are not expected to significantly affect the results in the figure. The rotational speed of the turbine is indicated in the x axis, the measured frequencies are along the y axis, and the energy content in a measured frequency is indicated by the colour.

In rotating 3-bladed turbines, it is expected that the system will experience forced excitations at 1P, 3P, and to a small degree 6P, where "XP" indicates a forcing that is X times per revolution. 1P excitations occur due to, e.g., mass imbalances in the rotor; 3P is driven by shear, tower shadow, and turbulence sampling; and 6P is a higher harmonic of shear, tower shadow, and turbulence, etc.

Because these three harmonics inject energy into the rotating system at these frequencies, they are indicated in the waterfall plots as straight lines. If an excitation frequency overlaps with a natural frequency with low damping, it can cause undesirable vibrations in the system that must be monitored or avoided.

In the first OrcaFlex simulations, it was observed that the 3P excitation frequency was overlapping with a structural model at high rotation speeds, which was causing undesirable resonance in the system. This is indicated by the "B" point in the right plot of Figure 14, where the 3P line crosses the structural mode and creates a lot of vibration energy, indicated by the dark red colour. Although the vibrations in the simulation results were well below safety thresholds, it was still of interest to validate this phenomenon in the installed platform.

The waterfall diagram from the experimental run-up test is shown in the left of Figure 14. As indicated by the colours near the 3P excitation line, there is only a minor amplification in the resonance area. This could for example be due to higher damping of the physical system or less shear across the rotor than in simulation, which would reduce the energy content in the 3P signal. It could also be that the energy transmission mechanism from the excitation into the eigenmode is weak, thus not leading to a severe amplification. The potential resonance issue is thus determined to be not a significant concern, although it will be continued to be monitored in the continued operation of the turbine.

In the experimental waterfall plot, there was seen an unexpected amount of energy in one of the rotor modes, excited by the 6P frequency. One potential reason for this not being reflected in the OrcaFlex simulation is that there is no tower shadow in the OrcaFlex simulation, but the two masts could cause more excitation in the 6P harmonic than a single tower alone. After discussions with the manufacturer, it was determined that this vibration issue has also been observed to a small degree in onshore installations, and so to reduce fatigue the frequency band should be avoided if possible. Thus, the turbine controller will be operated such that the frequency band where 6P overlaps with this rotor mode will be avoided.
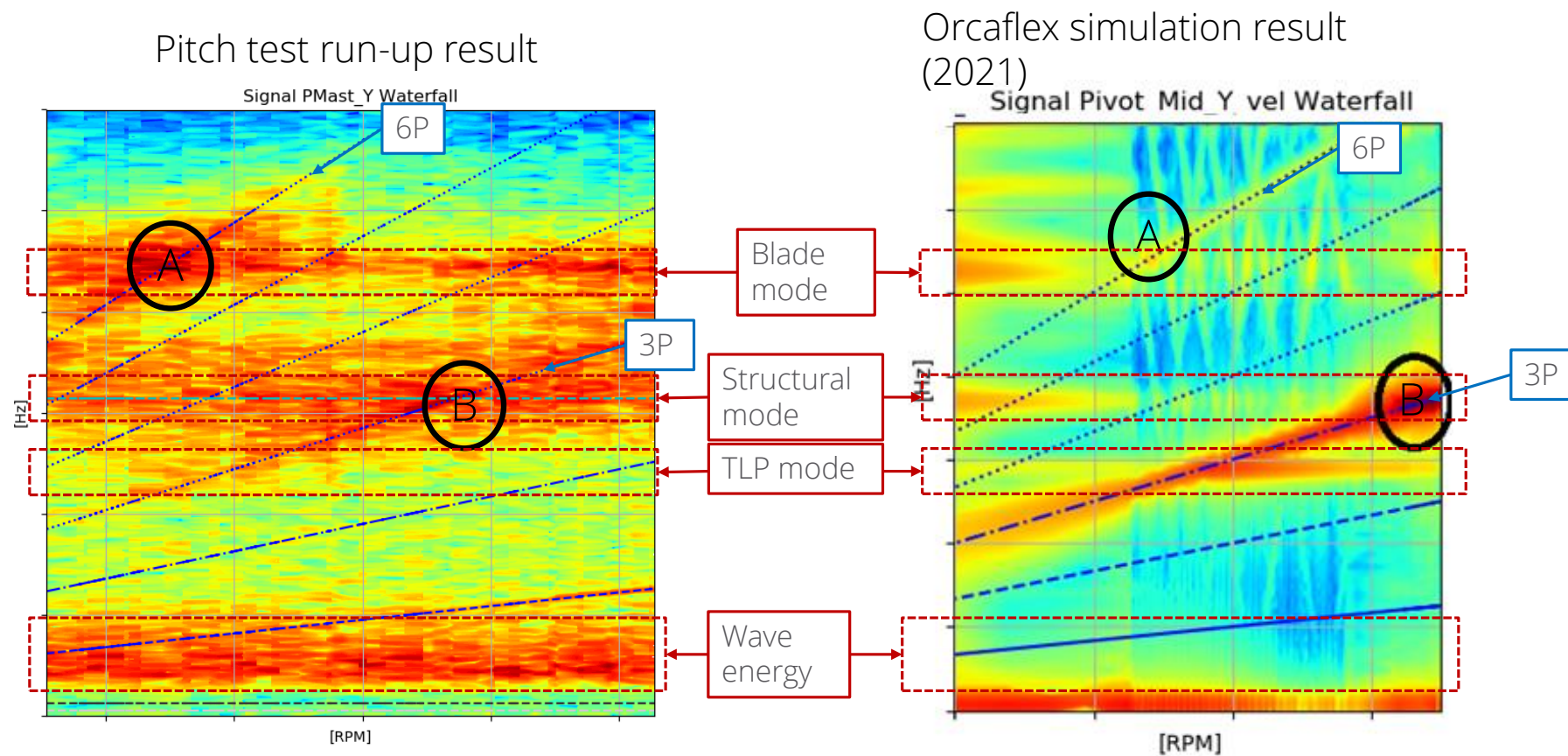
Figure 14: Waterfall plot of pitch test run-up (left) and OrcaFlex simulation result (right).

6 FUTURE WORK

The validation work presented here has resulted in significant knowledge gained, both in understanding of the softwares during the cross-validation as well as in the sensitivity of the platform performance to different conditions. Although the tasks in this work package are ending, there have been several tasks identified as future work:

1. **Validate with operational data**. As the data was unavailable at this time, the validation with normal operational data is planned for the final report.

2. **Fixing platform yaw drift in HAWC2 for non-operating case**. The exact cause of the lateral force on the main columns is currently unidentified, but it has been attributed to the Morrison calculations. The PivotBuoy work for DTU ends after this deliverable, so any fixes in the hydrodynamics will likely not be available for the final report. However, DTU is a member of the NEXTFLOAT project, in which a similar platform will be simulated in HAWC2. Thus, the validation work presented here is a good preliminary test case for the work in NEXTFLOAT.

3. **Investigate cause of platform yaw overshoot**. As noted in Sec. 5.2, the OrcaFlex model tends to react more quickly to changing wind direction than the X30 platform, resulting in an overshoot when comparing the yaw signal. Because the model yaws more quickly than the true platform, the platform misalignment is reduced and there is less wind-induced excitation in the simulation roll. This difference in yaw damping could be due to multiple reasons, including the lack of yaw-bearing friction in the model or small differences in the hydrodynamic damping of the platform. A potential future investigation could look into the cause of this in more detail to identify and tune the relevant parameters. However, this phenomenon is only relevant for a non-operating case, because the thrust of an operating turbine would increase alignment significantly. The non-operating situation is generally less relevant for the platform in terms of loads and power production, and thus this analysis may be omitted in favor of analyzing production data.

7   CONCLUSIONS

The X30 platform is an innovative floating offshore wind platform with a downwind rotor that passively yaws around a single-point mooring. The platform has been designed using site-specific simulations for the installation site at the Oceanic Platform of the Canary islands, and its performance has been previously simulated and analysed using HAWC2 and OrcaFlex.

During the manufacturing process, some small changes were made to the design and thus the HAWC2 and OrcaFlex models needed to be updated. A simple cross-verification was completed that compared the total mass, centre of gravity, and other static parameters to verify that they matched to an adequate degree of accuracy. The models were further cross-verified by comparing floater frequencies calculated with eigenanalyses (OrcaFlex) and a combination of free decays and eigenanalyses (HAWC2). The results showed significant discrepancies in the frequencies, ranging from 4% to 16%, even after some tuning efforts of the HAWC2 model. It was decided to accept these values and use the remaining resources on the validation.

The turbine is unfortunately not commissioned at the time of this writing, so the validation must focus on non-operational data and a short run-up test. Validation of production data will be presented in the final report.

The first validation test was a one-to-one validation comparing the response of the non-operating platform to measurement data acquired on January 22, 2023. The preliminary simulations were completed first in OrcaFlex, as the HAWC2 floater frequencies were in the process of being tuned. The first OrcaFlex simulation included a single wave swell based on the measured wave parameters and wind time series extracted from the data. The results were adequate but showed some discrepancies in the platform pitch mean value due to the tide and in the energy content of the platform pitch frequencies indicating the presence of a secondary swell with a higher period.

A second validation was thus conducted with an updated tide parameter and the inclusion of a secondary swell based on forecasted data. For this secondary simulation, HAWC2 results were also compared, albeit with only a single swell as the software does not permit secondary swells.

The HAWC2 yaw signal did not match the data particularly well, revealing an offset in the signal that decreased with increasing wind speed. After significant debugging, this was found to be caused by a bug in the calculation of the Morrison hydrodynamics, which causes a small lateral force on the main columns. For larger wind speeds or an operating turbine, this drift is not noticeable. However, because the one-to-one validation used non-operational data, the drift is significant. Because the HAWC2 yaw does not match the experimental yaw, the HAWC2 results do not match the data in any of the analysed signals. The issue will be addressed as part of DTU's participation in the NEXTFLOAT project, which is a continuation of PivotBuoy.

The OrcaFlex results match the data extremely well. The mean value of the platform pitch matches almost exactly, and the energy of the wave spectrum in the simulation is significantly improved over the single-swell case. The roll signal matches also quite well in the beginning of the simulation, but the simulation does not capture some low-frequency energy in the latter part. This is hypothesized to be due to a change in current during the measurement window, which slows the yaw motion and

increases peak loading due to the wind. However, this phenomenon will only be present in a non-operating case and is therefore not pressing.

A final investigation into resonance was presented using data from a short pitch run-up test conducted in early March. Previous OrcaFlex simulations raised a potential concern of an overlap of the 3P excitation frequency with a structural mode, resulting in undesirable vibrations. The pitch run-up test did show a resonance but it seems highly damped, leading to minimal amplification; thus, the performance of the platform is better than predicted. Some unexpected vibration was detected in the run-up test, which was attributed due to a rotor mode interacting with 6P. After discussions with the manufacturer, it was determined that this interaction is a known phenomenon, and the turbine will be operated during future production to avoid this resonance band.

The objectives of this deliverable are fulfilled. The model is determined to be validated, and through extensive discussions and simulations on the results for the eigenanalyses and the one-to-one validation, the consortium has been able to deepen their understanding of the platform performance both in modelling and simulation.

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