Executive Summary

Thesis

submitted for the degree of Master in Marine Technology
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in the EMship+ Advanced Ship Design Course

New technology demonstration project for a floating offshore wind turbine foundation with guy wire supported tower

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Abstract

A floating offshore wind turbine (FOWT) concept with a guy wire supported tower was investigated to obtain results on its elastic response characteristics in waves. The joint research project, of which the Ocean Space Planning Laboratory of the University of Tokyo is a project partner, is initiated by the New Energy and Industrial Technology Development Organization (NEDO). The concept aim is to lower the cost of FOWTs by using a lightweight structure tensioned with guy wires and a downwind turbine concept. Thereby, the whole floater is a weatervane system, adjusting itself into the wind direction around a single point turret mooring.

A wave tank experiment was carried out at the offshore structure testing tank of the National Maritime Research Institute (NMRI) of Japan with a dynamically and elastically similar backbone model. The objective was to obtain the response of the structure due to the incidence of regular and irregular waves in different encounter angles as well as with and without wind simulation. The floater six degree of freedom body motion, the tension in the guy wires and also the strain in the structure were measured. The rotor nacelle assembly (RNA) was replaced by a duct fan simulating the force acting on the system by wind drag and turbine thrust.

The obtained motion responses of the floater showed a large coupling of the pitch motion at its natural period response with every other degree of freedom. The obtained heave natural period as well as the heave cancellation period match thus large motions responses are avoided in this period range.
Tests with an implemented drag force and without showed very similar results in the responses. Waves encountering the structure from the side result in large yawing motions. This is also the case when a drag force is implemented indicating a desire of the structure to turn into the wave direction. The irregular wave tests response amplitude operators show a similar response as the results obtained from the regular wave tests. The accelerations and pitch angles at the turbine nacelle are below usual design values for the whole period test range.

The RNA mounted on the top of the floater is implementing loads and inertia forces. The obtained responses of the system were investigated to conclude on the effect of the guy wires and the load transmissions in the floater.
The wires were not sagging during the whole experiment and a combination of tower, floater arms and guy wires respond to the forces in a hydroelastic behavior. The waveward bending moments correspond the most to the surge motion, which is the same for the two leeward guy wire tensions. Contrary, the leeward bending moments correspond most to the pitch motion, same as for the forward guy wire tension.

Moreover, a brief numerical analysis of the floater motions was carried out in the boundary element code WAMIT. The strong coupling of the pitch motion towards all other degrees of freedom was confirmed.

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Un grand merci à tous ceux qui ont aidé et soutenu.
Herzlichen Dank an alle, die geholfen und unterstützt haben.

1 Introduction

With a globally rising demand for energy, floating offshore wind turbines (FOWTs) open the opportunity to harvest resources further offshore where the wind quality is better and the turbine is out of sight from the consumer. Compared to fixed bottom offshore wind turbines, FOWTs did not reach the same level of standardization yet. But, as the market is aiming towards deeper waters, floating offshore wind parks might become cost competitive with technological advances. Therefore, this research seeks to expand the usage of floating offshore wind technologies by testing a new concept named OPTIFLOW.

The OPTIFLOW floating offshore wind turbine concept is a joint project led by the New Energy and Industrial Technology Development Organization (NEDO) on a new generation offshore wind power system.

1.1 Project overview

The concept studied in this thesis is a lightweight floating offshore wind turbine with a guy wire supported tower. It was initiated by aerodyn and has been refined several times resolving in the company holding several patents regarding this technology nowadays [1]. Currently, the development of the OPTIFLOW is carried out as a joint project led by the New Energy and Industrial Technology Development Organization (NEDO). NEDO is a management agency focusing on research and development. They are cooperating closely with the Ministry of Economy, Trade and Industry in Japan (METI) [2]. The study is carried out to evaluate a possible new addition to the testing site of the already installed Hibiki-barge FOWT north of Kitakyushu, Japan. On this specific location, the water depth is about $56m$.

1.2 OPTIFLOW concept description

The OPTIFLOW concept falls into the category of a semi-submersible column-stabilized type floating offshore wind turbine. In Figure 1 a sketch is presented showing the concept idea.
The floater itself has arms in a Y-shape, each arm consisting of a metal structure with tanks and placed in 120° angles towards each other. At the end of the arms, columns are facing straight upwards. At the center of the structure a column is standing out to hold the tower of the wind turbine. On the top of the tower the wind turbine generator (WTG) is placed. From each column a guy wire is attached to the upper end of the tower, tensioning the system. The tower is slightly inclined backwards, to avoid contact of the guy wires and the blades during energy harvesting.
The wind turbine generator with its blades is facing leewards from the wind direction, meaning this FOWT has a downwind turbine concept. In order to ensure the turbine is facing the wind direction in the right way, the whole structure is supposed to turn into the wind. This turning is provided by the turret mooring at the bow column of the FOWT. This way, the structure can rotate around the turret in a weather vane manner without twisting the mooring lines and into the direction of the wind.

The overall dimensions of the full scale prototype are presented in Table 1. The aim is to implement a two-bladed aerodyn SCD advanced 6 MW WTG with a diameter of $140m$ [3, 4]. The rotor nacelle assembly (RNA) is supposed to weigh $450t$ in total.

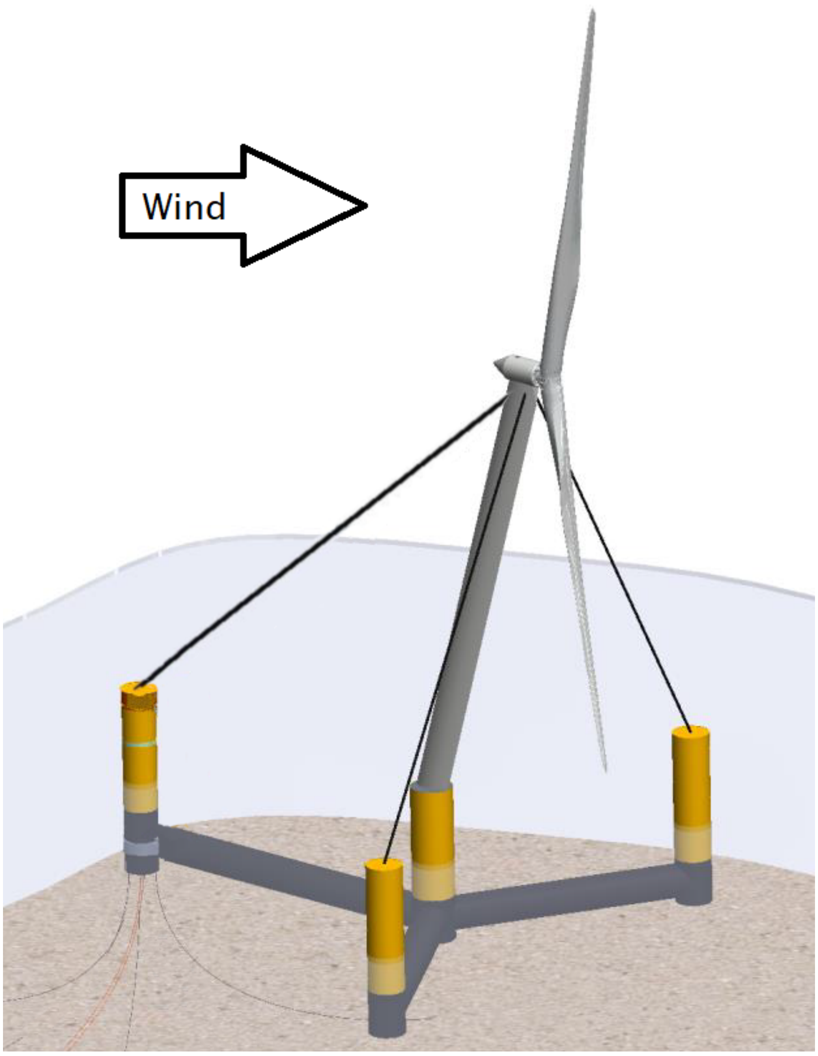

Figure 1: Concept idea of the OPTIFLOW offshore wind turbine floater.

1.3 Objectives of the concept

Apart from all the good will of lowering climate change consequences by using renewable energies, the main driver are industrial benefits as an alternative to current main energy sources and as income. As described by [5], wind energy is still more expensive overall than other energy sources, thus cost reduction is the main goal in their development.
The OPTIFLOW concept aims to lower costs to ¥$20/kWh$, mainly by reducing the weight, as well as by reducing the installational and operational costs [3]. Exemplary explanations of concept specifications that strive to achieve this are as follows:

- By implementing a downwind system where the structure passively swivels around the turret mooring, tuning between the WTG and the foundation can be avoided. This can lead to cost and failure reduction in tuning the WTG position, and systems to align floater, wind and turbine are omitted.
- A two-bladed WTG is implemented in order to reduce weight, as well as production, installation and maintenance cost. Also, the aim is to reduce the failure rate of the blades, especially regarding the hub and pitch systems, compared to three-bladed

WTGs. Thus, with also the yaw drive being omitted, the reduction of systems in the nacelle results in a lightweight and compact solution.

- The guy wires are tensioned wires holding the tower at its position. This results in the floater needing less supporting structure to be stable which makes it an overall lighter system. Also, the draft can be reduced which makes application in shallow as well as in deep water possible and simplifies production and installation.

1.4 Preceding concept: SCD-Nezzy

A very light semi-submersible floater of a similar concept to the OPTIFLOW has been investigated prior in 2017 at the University of São Paulo, Brazil, which was publicized in [6, 7, 8, 9]. The structure consists of three equally spaced offset columns which are connected in their center by pontoons to a straight tower. This central tower is connected to the three columns by guy wires allowing the structure to be light. The model tested is a segmented backbone model with a scale of 1/80.

2 Procedure

The OPTIFLOW floating offshore wind turbine concept was scaled down to a model for experimental testing in a water tank.

2.1 Experimental model description

The OPTIFLOW semi-submersible floating offshore wind turbine concept is scaled down to a model that is used for experimental wave tank testing. The model is a segmented-backbone-model, meaning it is divided into several connected structural parts. The model is scaled with geometric similarity according to Froude scaling and with a ratio of 1/60. For the construction of the model, the geometry of the FOWT, the flexual rigidity of the vertical tower as well as the hydrostatic and hydrodynamic behavior of the floater are taken into account. The overall dimensions of the model are presented in Table 1.

Table 1: Overall dimensions of the OPTIFLOW floater and the model.

Dimension		Full scale		Model scale	
Overall length	L	90.28	m	1.50	m
Overall breadth	B	92.94	m	1.55	m
Height to nacelle	D	109.80	m	1.83	m
Draft	T_D	14.75	m	0.25	m
Displacement	Δ			30.999	kg

The actual model as build is presented in Figure 2. The arms of the lower hull, as well as of the tower are divided into four connected elements around a core beam. The divisions are made of urethane and the core material is stainless steel. The columns are connected to the tower top by pretensioned guy wires. The instrumentation of the OPTIFLOW model is shown in Figure 3 with the labeling of each measurement device.

Figure 2: Model as build.

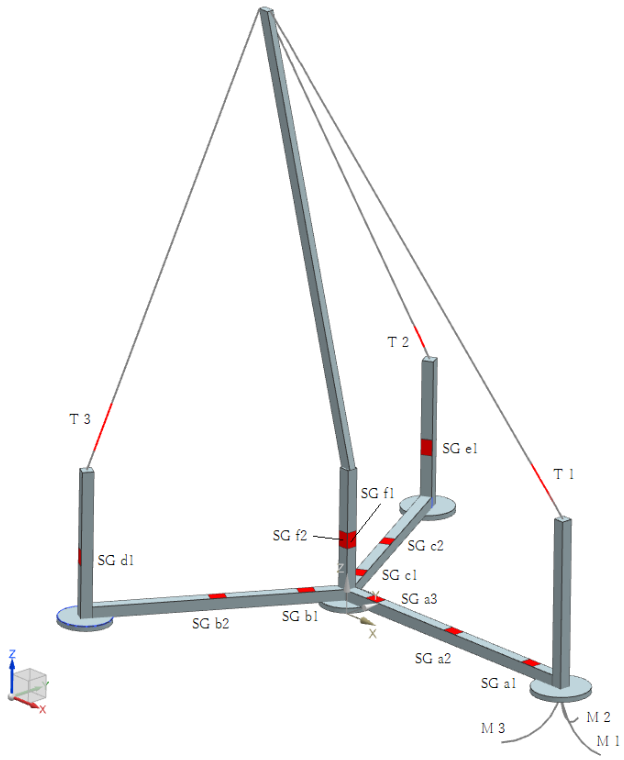

Figure 3: OPTIFLOW model core metal frame strain gauges (SG), mooring (M) and guy wire (T) tension meter location and labeling.

In order to grasp the floating body response when wind loads are applied, a duct fan provided by Osaka Prefecture University is implemented on the model at the place of the turbine nacelle in full scale. During tests with different wind settings, the sum of the wind drag acting on each part of the floating body below the nacelle and the thrust force of the turbine are taken into account. The wind speed of $11m/s$ is a strong breeze and the maximum operational condition of the wind turbine. The imitated wind speed of $41.9m/s$ is the typhoon condition where the turbine does not operate.

2.2 Wave basin experiment

The floating offshore wind turbine model OPTIFLOW described above was tested in a water wave tank that can carry out regular and irregular wave tests in one direction. This test facility is described here, as well as the actual experiments performed.

2.2.1 Test facility description

The testing was carried out in the offshore structure testing tank of the National Maritime Research Institute (NMRI) of Japan and is described in [10]. The setup of the OPTIFLOW model in the offshore structure testing tank at the NMRI is presented in Figure 5 as a top

view including the facilities of the wave basin. The water depth implemented is $93cm$. Different tests were carried out, where most waves came from forward direction, meaning the test was carried out in head waves. Nevertheless, some tests were carried out in side waves to test extreme conditions. The positions therefore are presented in Figure 4.
For some tests, counterweights were installed to maintain the yaw direction. They are of $200g$ each and installed at both bow and stern of the model.

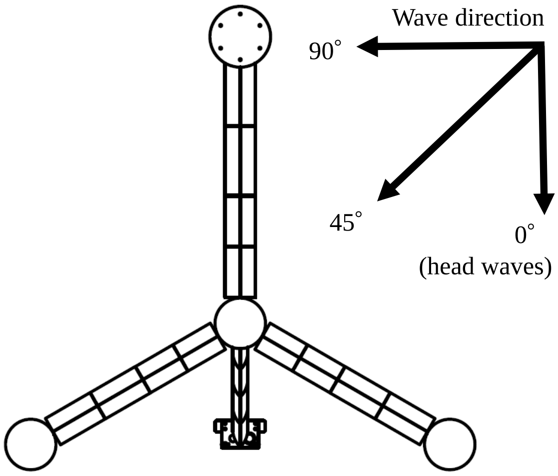

Figure 4: Different wave encounter angles of the OPTIFLOW model.

2.2.2 Test program

In the scope of the experiment different tests were performed. The wave experiments were carried out as stated here and not repeated. The following tests were carried out with the wave characteristics given in model scale:

1. Swing test
2. Inclination experiment with mooring
3. Mooring characteristics test in x- and y-direction
4. Decay tests in surge, heave, roll and pitch with mooring
5. Decay test with counterweight in surge, pitch and roll with mooring
6. Hammering test
7. Regular wave tests in head waves:
   - Wave periods: $0.6s$ to $3.8s$
   - Wave heights: $30mm$, $60mm$ and $90mm$
8. Regular head waves test with wind:
   - Wave height: $60mm$ ($3.6m$ in full scale)
   - Wave periods: $1.0s$ to $2.6s$
9. Regular wave test with waves from different side angles:
   - Wave height: $30mm$ ($1.8m$ in full scale)
   - Wave periods: $1.4s$ to $2.6s$

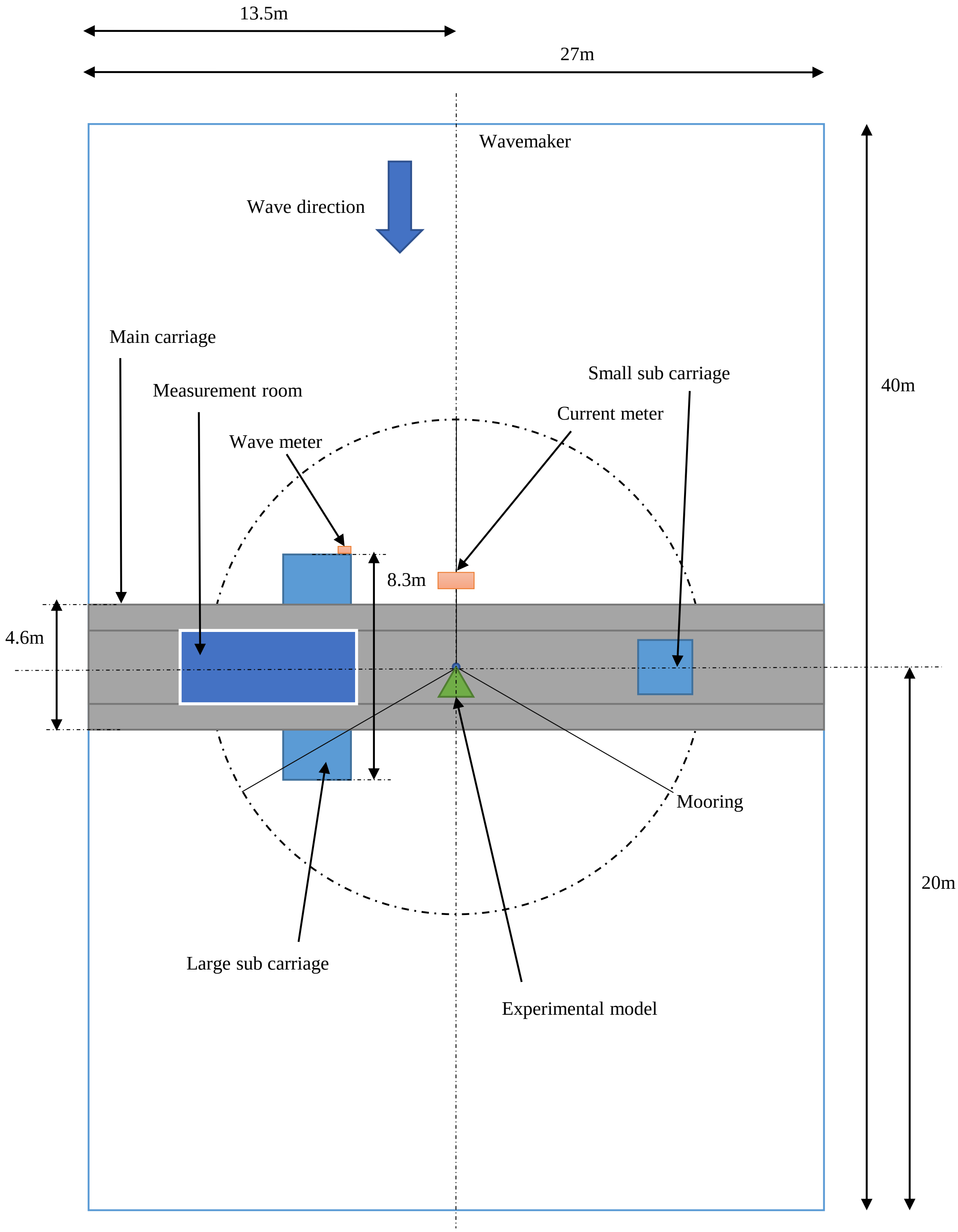

Figure 5: Overall top view of the offshore structure testing tank setup with the model.

10. Regular side waves tests with wind:
    - Wind speed: $11m/s$ ($3.248Ns$)
    - Wave height: $60mm$ ($3.6m$ in full scale)

- Wave periods: 1.8s to 2.6s

11. Irregular wave tests (in head waves):
    - Spectrum: ISSC
    - Testing time 24min (3h full scale) divided into two testings with a duration of 12min each
    - Tests performed:

Conditon	Model scale		Full scale	
	T_p $[s]$	H_s $[mm]$	T_p $[s]$	H_s $[m]$
Operational	1.162	41.67	9.0	2.5
Storm	1.743	163.33	13.5	9.8
Centenary	2.079	66.67	16.1	4.00

3 Results

The main results obtained from the experiments were: the first order motions of the floater, the tension fluctuations in the guy wires, as well as the bending moments at different locations on the structure. The results are given for the full scale.

3.1 Motion response

The natural periods obtained from the decay tests are presented in Table 2 for the test without and with counterweight to implement a stiffness in the yaw direction. The model inertia in roll is $7.36E+06tm^2$ and in pitch $1.04E+07tm^2$.

Table 2: Natural periods obtained and damping factors.

	Surge	Heave	Roll	Pitch	Yaw
Natural period with counterweight $[s]$	39.66	-	-	22.70	158.64
Natural period without counterweight $[s]$	35.77	17.60	34.34	21.98	-
Damping coefficient $[-]$	0.008	0.120	0.034	0.072	-

Response amplitude operators (RAOs) of the regular wave test motions are presented in Figures 6, 7 and 8. If not stated otherwise, the wave direction is always head waves.

3.2 Guy wire tension and bending moments

In Figures 9 to 14 guy wire tensions are presented as well as bending moments at the tower. The tower of the structure has the RNA mounted on its top. As the load and the inertia force have to be supported, the guy wires are supposed to support the structure in this concept.

3.3 Accelerations at the turbine nacelle

Exemplary accelerations at the turbine nacelle from the regular wave test experiments are presented in Figure 15.

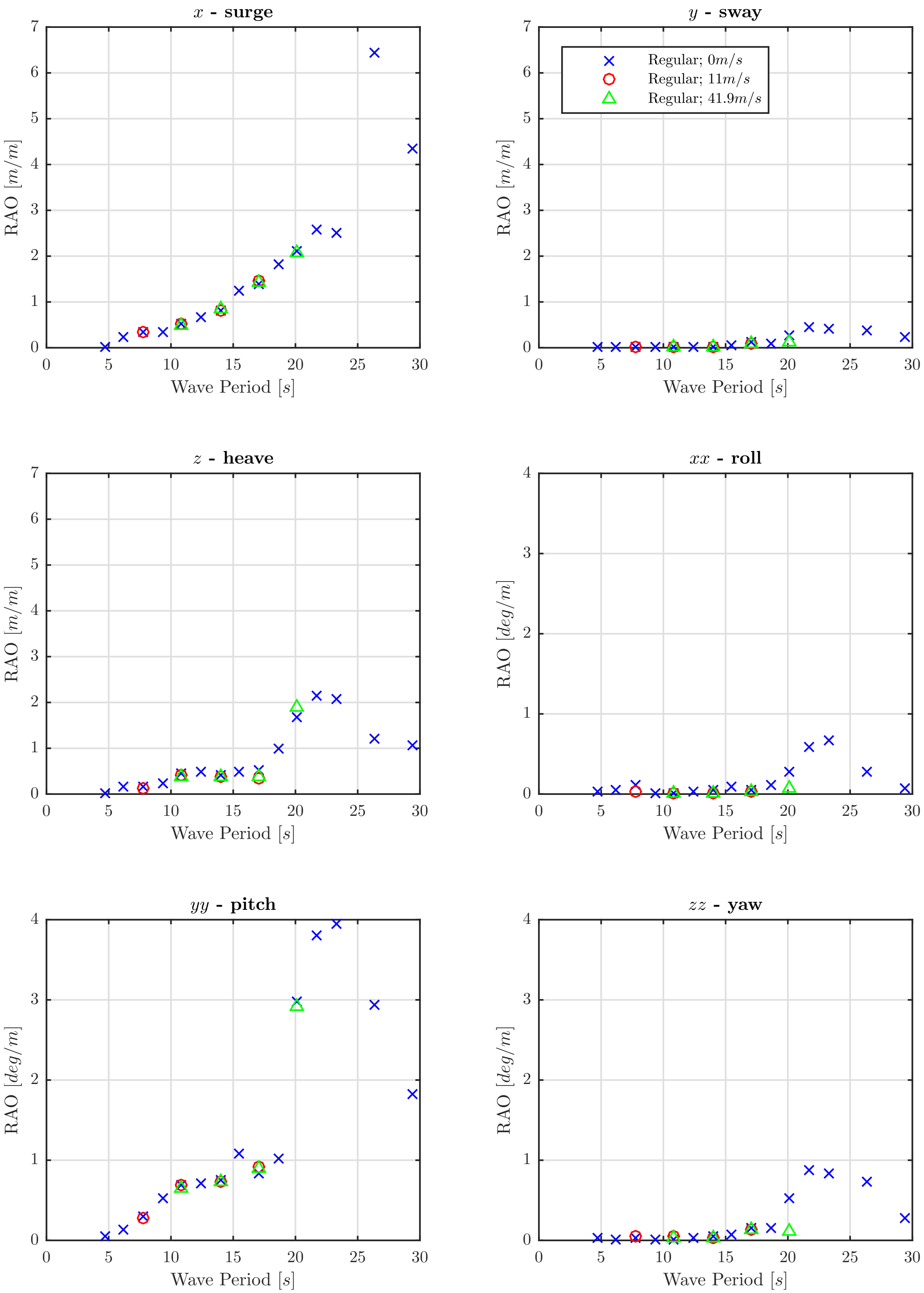

Figure 6: Motion RAOs of the regular wave test in head waves and different wind speeds.

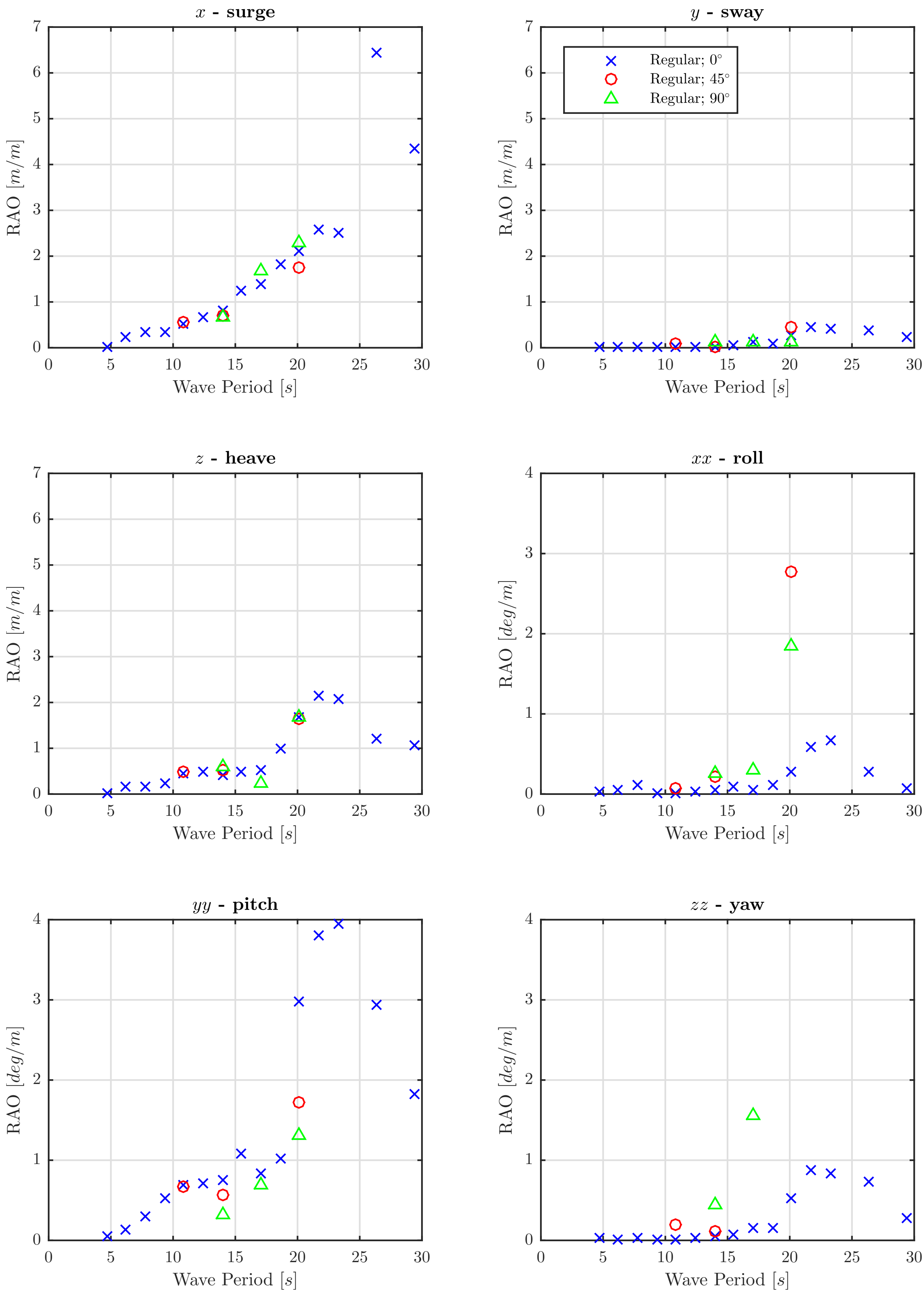

Figure 7: Motion RAOs of the regular wave test in waves with different encounter angles.

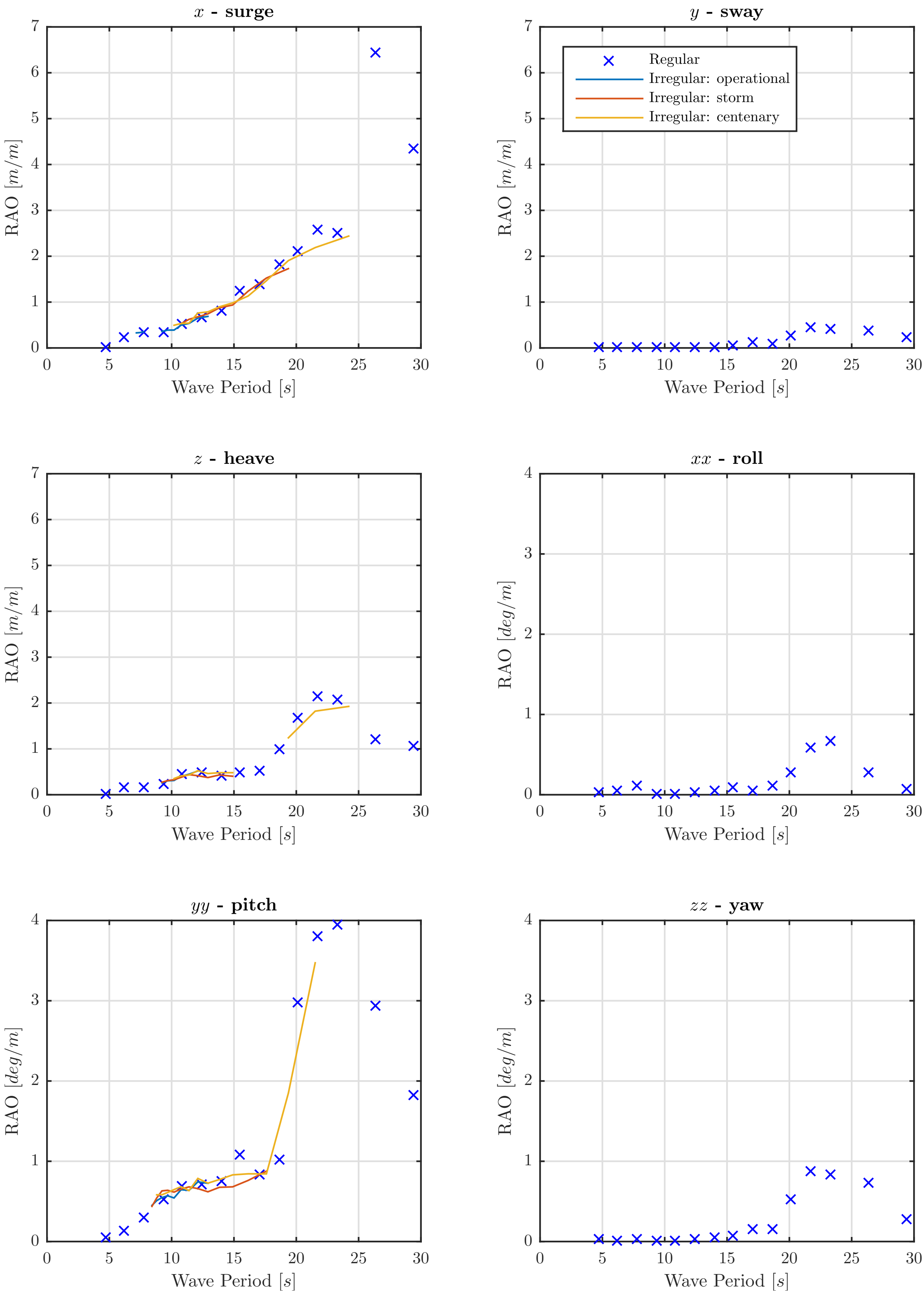

Figure 8: Motion RAOs of the irregular wave test in waves with different encounter angles and with wind.

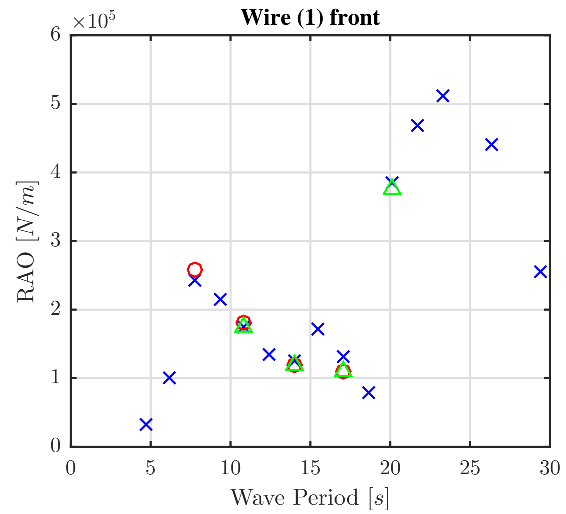

Figure 9: Wire tension RAOs for different wind speeds.

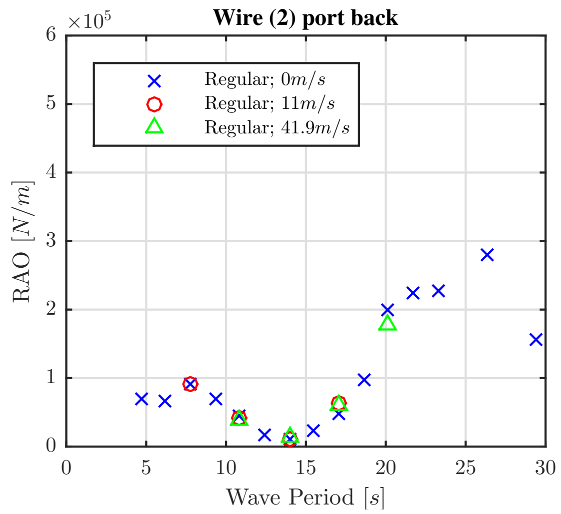

Figure 10: Wire tension RAOs for different wind speeds.

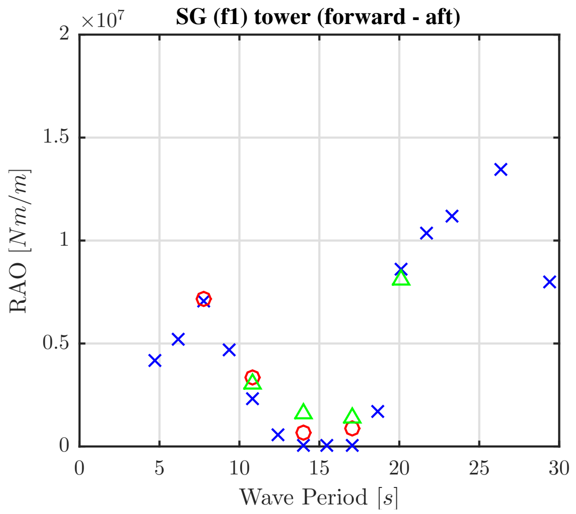

Figure 11: Bending moment RAOs for different wind speeds.

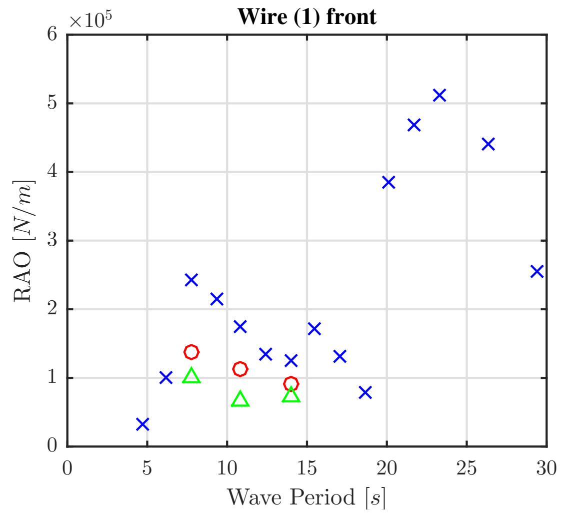

Figure 12: Wire tension RAOs for different encounter angles and with wind.

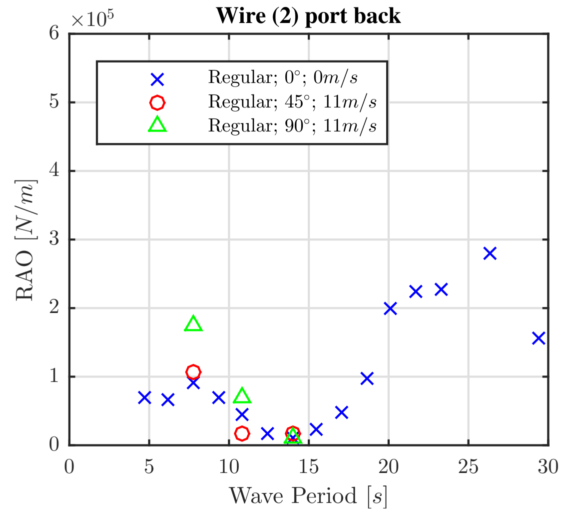

Figure 13: Wire tension RAOs for different encounter angles and with wind.

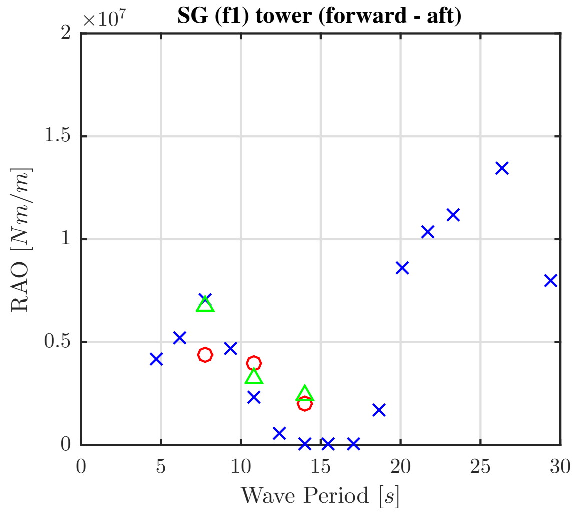

Figure 14: Bending moment RAOs for different encounter angles and with wind.

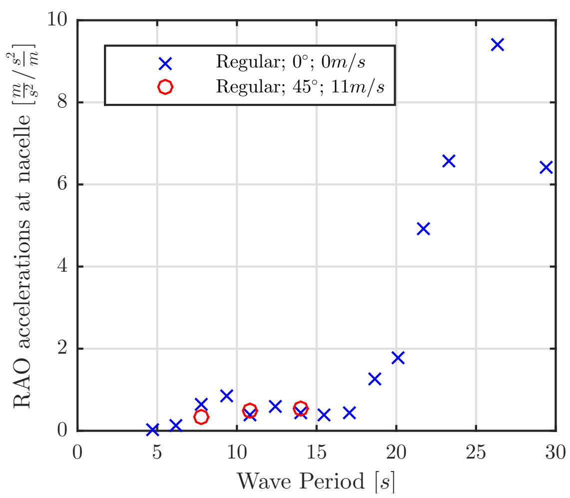

Figure 15: RAOs of accelerations at the turbine nacelle for different wave encounter angles.

4 Conclusion

The main natural periods of the moored floater motions are 35.77s for surge, 17.60s for heave, 34.34s for roll and 21.98s for pitch. Different regular wave tests in head waves were carried out, for different wave heights and with different wind speeds applied. Also, three different irregular wave tests were carried out. The main findings regarding all response amplitude operators and especially the motion amplitudes are:

- Response amplitude operators obtained for regular wave tests in different wave heights resulted in very similar values. Thus, nonlinearities seem rather small in the here tested period range from 10.84s to 17.04s.

- The heave natural period was not confirmed by the wave tests, as its response motions show a large coupling with pitch and no peak around this period was obtained. This is obtained for all responses of the floater, as this period corresponds to half the wavelength that is equal to the floater length projected in the wave direction. Most likely, the heave natural period is meeting the cancellation period that a semi-submersible response function contains. This hinders large heave responses.
- The pitch natural period was confirmed by the different tests carried out, as the response amplitude operator plot shows a significant peak around this period. The pitch motion is strongly coupled with every other degree of freedom. The large pitch motion and its strong influence might come from the asymmetry of the structure about its y-axis. Another reason can be the unfavorable influence of the cables attached to the measurement devices.
- The wave tests with sideways wave encounter angles showed large yaw motions which were supposed to be suppressed by a counterweight. This yaw motion influences the behavior of all other motions. On the other hand, it shows that the structure wants to turn into the wave direction. This is also the case for this test carried out with an applied wind force in the x-direction of the floater itself.
- No significant change in the RAOs of the regular wave test for tested with and without wind were obtained.
- The irregular RAOs show a similar response as the regular waves test results. This usually means that that there are only rather small nonlinearities in the model.

The mooring line tension fluctuations are mainly influenced by the pitch and surge motion. Responses in waves with large periods are considerably higher. The forward mooring line takes the largest forces, but the two rear lines also show significant amplitudes close to the responses of the forward mooring line. The front mooring line shows the overall largest response that is probably coupled to surge motion.

The tower of the structure has the RNA mounted on its top. As the load and the inertia force have to be hold, the guy wires are supposed to support the structure in this concept. Regarding this, the following main observations were made:

- No slack of the guy wires was detected during the experiment confirming the pretensioning.
- A combination of tower, pontoon arms and guy wires seems to hold the inertia force of the RNA at the tower top during all wave test. Thus, a hydroelastic behavior is present.
- The wire tensions fluctuations are mainly caused by pitch, but also the surge motion has an influence in large periods. Wire tensions and tower bending moments are larger in longer period waves as the overturning moment of the tower caused by large inclination becomes large.
- The forward guy wire generally takes the largest force, but is strongly supported by the rear wires.
- All bending moment measurement positions are influenced by the pitch motion response. This is especially present for the forward arm bending moment and the forward to aft direction bending moment at the tower top. These locations are also strongly influenced by the largest surge amplitude measured.

- The front arm bending moments correspond the most to the surge motion, which is the same for the two rear guy wire tensions. On the other hand, the rear arms bending moments correspond most to the pitch motion, same as for the front guy wire tension. The tower bending moments in front and aft show a broad peak in its transfer function indicating a coupling of both motions together with the wire tension fluctuations as well as the pontoon arms.
- The tower bending moments as well as the guy wires actually decrease in response for the tests carried out with an applied drag force at the tower top. A slight increase in bending moment can only be observed in the response of the rear pontoon arms measured directly at the tower.
- During the tests with an applied drag force a slight increase can be observed in the tower forward to aft bending moment in the period range between $12s$ to $20s$. The wire tensions, on the other hand, stay the same as for the test without the wind force. This might implement that here the additional force is mainly taken by the tower.
- Test with waves from different encounter angles were performed. The bending moments at the tower bottom were actually lowered or stayed the same as for the head waves tests. Nevertheless, the tension in the rear wires changed synchronized. This indicates that the guy wires support the structure to a large extend.
- The yaw motion seems to affect especially the rear wires tensions in side waves. Especially when a wind force is implemented due to the thruster, also the tower bending moment increases. This hints a large influence of the tower in taking the loads implemented by the wind and the turbine.
- In sum, the responses of the guy wires and the tower bottom, as well as the whole floater, are coupled. The model is elastic and the load of the RNA is distributed over the whole structure.

The accelerations at the turbine nacelle are mainly caused by the surge motion of the floater. Also, the pitch motion has a large influence and huge responses are mainly obtained in large period waves. Accelerations as well as pitch motion at the turbine nacelle are below the maximum design values for the cases tested.

The numerical calculations carried out in WAMIT confirm the strong coupling of the pitch motion towards all other degree of freedom motions. Also, the heave cancellation period seems to be at the heave natural period thus avoiding a response. Further smaller nonlinear effects in the experimental results can be determined due to the consideration of a rigid model in the linear program executed.

In order to draw conclusions on the applicability of the concept, further numerical studies need to be carried out, to validate the results obtained, especially with regards to the guy wire's functionality.

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