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Motion Response of a Floating Offshore Wind Turbine Foundation

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Abstract

Floating Offshore Wind Turbine (FOWT) is commonly used in harnessing wind energy in offshore regions. As a source of green energy, governments are paying more attention to the development of offshore wind farms worldwide. However, there are no offshore wind farms built in Australia. This study developed a conceptual design of FOWT based on the Bass Strait region which has the greatest potential for offshore wind farm development. Numerical simulations have been conducted using ANSYS AQWA to investigate the motion response of the concept in both the frequency and time domain. Both the uncoupled response amplitude operators and coupled motion behaviour were studied so as to determine an optimal design with respect to heave and pitch motions.

The results obtained from the investigation provided a good understanding of the motion response of the structure. Response amplitude operators found from the frequency domain simulations agreed with similar concepts in existing literature, while results from the coupled analysis showed that mooring lines could influence the response of the structure. Therefore, it can be concluded that the FOWT concept can safely produce electricity with a significant wave height up to 4 metres in the Bass Strait region.

Introduction

Along with the increment of world population, the demand for energy is increasing at the same time. It is predicted that by the year 2050 the world's energy consumption could be doubled [1]. Wind energy, a clean renewable energy source, is becoming more widely used throughout the world. The most common equipment applied in the transformation of wind power is the wind turbines, a majority of them are installed on-shore because of the relatively low initial investment and operational costs. However, the ideal wind farms are located in offshore waters where the wind is much stronger and more consistent in comparison to onshore. According to the renewable energy atlas of Australia, regions such as the Bass Strait may have the greatest potential for offshore wind farm development.

The aim of this study is to develop an innovative floating wind turbine concept and undertake a study into the motion response of the concept in a given sea state. The motion response of the structure will be analysed using a diffraction program, ANSYS AQWA. The scope of the numerical investigation incorporates:

- Determining free-floating response amplitude operators (RAOs) of the FOWT design for pitch, heave and roll motions in order to optimize the design
- Evaluating coupled motions of FOWT with a catenary mooring system in irregular waves for various wave headings
- Comparison of numerical simulation results with existing literature

Numerical Analysis

A numerical model of the FOWT was developed and analysed using ANSYS AQWA. The program is capable of carrying out static and dynamic simulations in both frequency and time domain, and determining the effects of coupling between structures and mooring lines and modelling linear and non-linear effects [2].

Definition of Environmental Conditions

The environmental conditions chosen for this investigation was based on the Bass Strait region in Australia. The Bass Strait is a stretch of sea between the states of Victoria and Tasmania, the average water depth of the region ranges between 50 to 80 metres. For the purpose of this conceptual study it is assumed that the water depth is 100 m. The JONSWAP wave spectrum was chosen to represent the wave environment in the region. The respective JONSWAP parameters [3] are shown in Table 1 with a significant wave height of 4 metres.

Significant wave height [m]	Zero-upcross wave period [s]	Peak period [s]	Mean frequency [Hz]
4	8	10.29	0.097

Table 1. Definition of environmental conditions

Geometric Optimization of FOWT

Taking a 5 MW wind turbine and the Bass Strait region as reference, a conceptual design of the FOWT developed by National Renewable Energy Laboratory (NREL) was used this study with its general properties presented in Table 2. The structure comprised of three main columns which are joined together by circular members, and the wind turbine is fitted in the geometric centre of the structure as seen in Figure 1. To reduce the heave response, each main column has a heave plate fixed at the very bottom.

Mass displacement [kg]	4,299,436
Volumetric displacement [m^3]	4,195
Operating draft [m]	15
Overall COG [x,y,z]	[0,0,5.58]

Table 2. NREL FOWT general properties

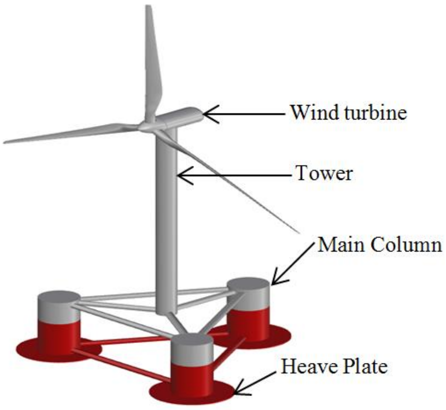


Figure 1. Geometry of the FOWT design

A parametric study on sizing the main columns and heave plates was conducted in order to determine the geometry of the FOWT obtaining optimal RAOs while maintaining constant displacement. The procedures of the geometry selection are demonstrated in Figure 2.

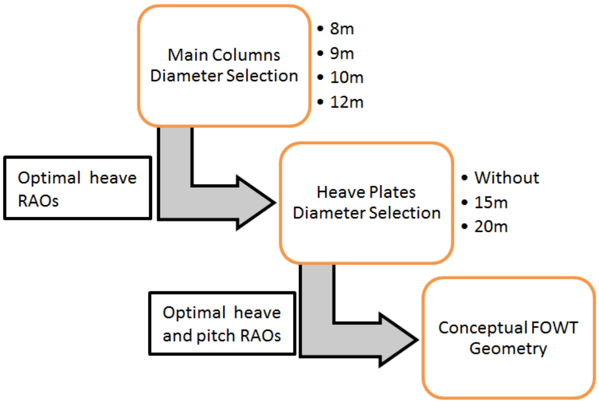


Figure 2. Geometry selection procedures

Coupled Motion Simulation

A catenary mooring system was added to the optimized FOWT design to simulate realistic coupled motion responses of the structure in the given sea state in Bass Strait region. The mooring system consists of 6 mooring lines distributed into 3 groups at an angle of 120º and the angle between the two chains in each group being 30º. The properties of the mooring lines are illustrated in Table 3.

Chain diameter [m]	0.078
Mass density [kg/m]	133.2
Stiffness per unit length [N]	520577460

Table 3. Catenary mooring properties

AQWA Simulation Setup

Before running the simulation, the structure was meshed with an element size of 1.2m as shown in Figure 3. Also the model definition and analysis parameters were specified depending on the type of analysis being conducted. The free-floating RAOs in the parametric study were calculated using AQWA-Line in the frequency domain while the couple motion response of the structure was analysed in the time domain using AQWA-Naut.

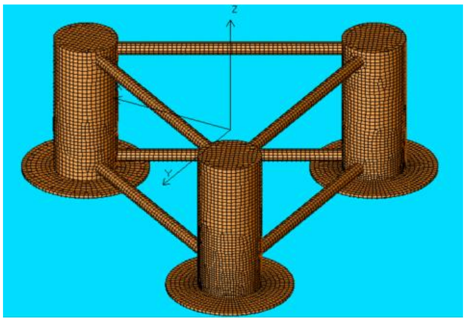


Figure 3. Meshed FOWT foundation structure

Results & Discussion

Parametric Study Results

In the parametric study, a general trend was observed whereby as the diameter of the columns increases, the heave response decreases from Figure 4. The maximum heave motions for designs with column diameter of 9 m, 10 m and 12 m appear at distinct frequency regions despite the similarity in their magnitudes. This is primarily due to the difference in the natural frequency of the structures, the larger the column diameter was, the higher the natural frequency appeared to be. These results are similar to that observed by White [4]. In this study, the 10 m diameter columns were chosen due to relative low heave RAO magnitude.

The second phase of the parametric study focused on the effects of heave plates on the platform motion. Using the 10 m column design as a base, two different sizes of heave plates were analysed and compared against a model with no heave plates appended. From Figure 5, it can be seen that the heave RAOs was reduced as the size of the heave plates was increased. These results agrees well with the findings from Seebai [5], whereby the addition of heave plates reduced the heave response. Similar results were obtained from the pitch RAO curves with respect to the heave plate sizes, where the largest heave plate size leaded to a significant reduction in the pitch response as shown in Figure 6.

Nonetheless it can be concluded from the parametric study that the optimal design for the semi-submersible FOWT is that of one which consists of 10 m diameter main columns along with heave plates of 20 m in diameter. This combination has result in a design that has low magnitudes of heave, pitch and roll.

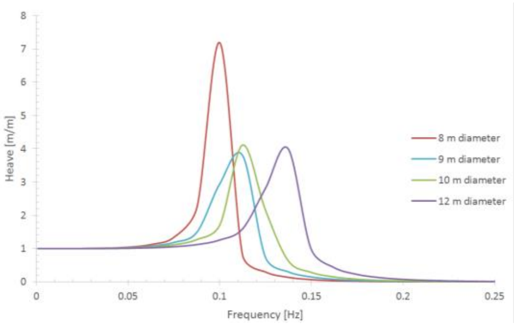


Figure 4. Heave RAO curves for various diameter columns

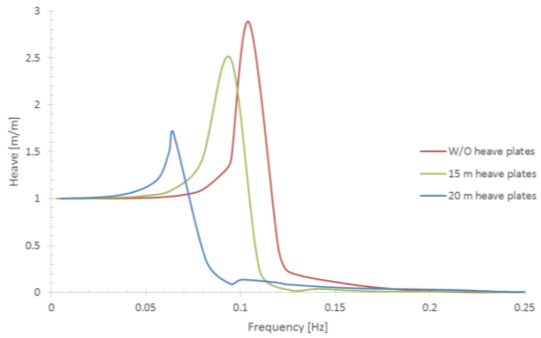


Figure 5. Heave RAO curves for various heave plate sizes

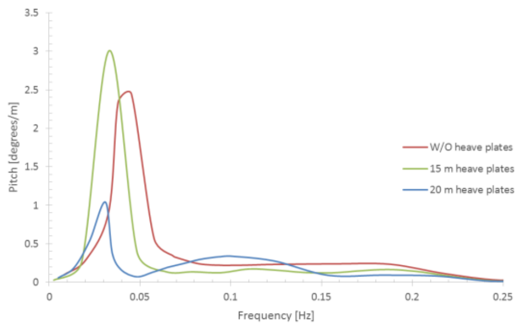


Figure 6. Pitch RAO curves for various heave plate sizes

Response Amplitude Operators

Using the dimensions from the parametric design study, an optimised concept design for the semi-submersible FOWT structure was developed. The heave, pitch and roll RAO curves of the design in various wave headings were calculated, shown in Figure 7, Figure 8 and Figure 9 respectively. It was observed that the heave, pitch and roll responses peaked at low frequencies. Also, it was observed that the encounter wave direction had a significant impact on the pitch and roll motion but not on the heave response of the structure. As can be seen in Figure 7, the heave RAO curves overlaps with each other. These results were comparable with previous studies by Bulder, Henderson et al. [6] and agreed well with the literature.

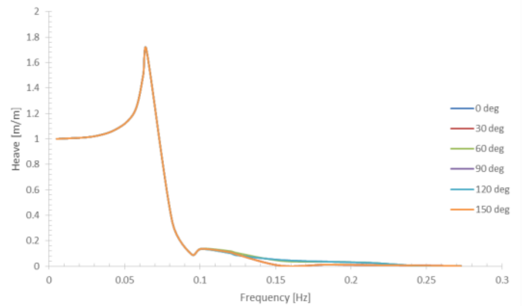


Figure 7. Heave RAO curves for various wave headings

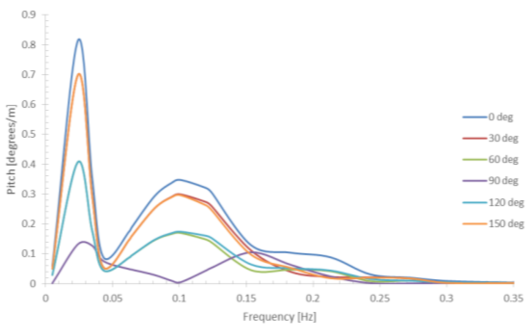


Figure 8. Pitch RAO curves for various wave headings

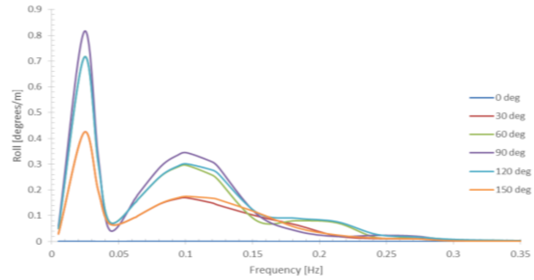
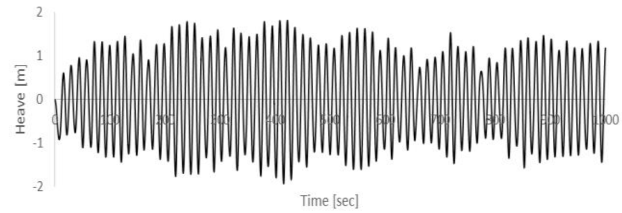


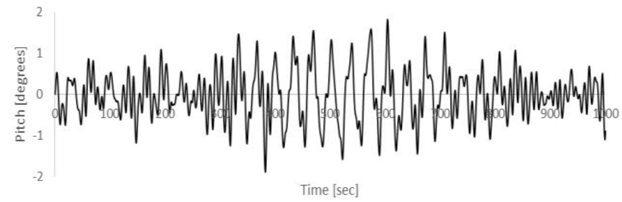
Figure 9. Roll RAO curves for various wave headings

Coupled Motion Analysis Results

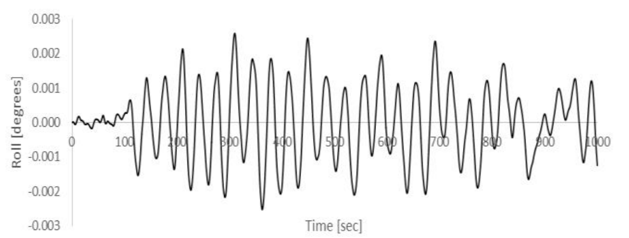
The coupled motion analysis was conducted to study the motion behaviour of the FOWT system along with mooring lines in an irregular sea-state. The motion of the structure was investigated with six headings along with a comparison outlining the effect that the mooring line properties could have on the response of the structure. Figure 10 shows the time history motion response of the structure in 4 m head sea waves. All of the simulations conducted were run for 1000 seconds in order to allow sufficient time for the motion behaviour to be captured and to observe any irregularities which would otherwise indicate an error in the time step. A time step of 0.1 seconds was used for the analysis. It can be seen from Figure 10 that all the motions appear to show a stable response with no irregularities.



(A)



(B)



(C)

Figure 10. Sample of time history motion (A. heave; B. pitch; C. roll)

In order to provide a better understating of where the main responses of the structure occur, a Fast Fourier transform was applied on the time history to convert the results into the frequency domain. Figure 11 shows the significant heave amplitude with respect to the wave encounter frequency. It can be seen that a peak heave amplitude of 1.0 m is at 0.072 Hz, and this peak indicates the natural frequency of the system. This natural frequency value is higher than that observed from the heave RAO curves shown in Figure 7. The shift in the natural frequency of the system is mainly caused by adding mooring lines to the system. The mooring lines put additional stiffness and mass to the system and therefore resulted in a shift of natural frequency.

Figure 12 and Figure 13 display the pitch and roll amplitude with respect to the frequency domain. As can be seen in Figure 12, the largest pitch amplitude of approximately 0.55° occurs when the incident wave direction is 0°, the lowest pitch amplitude was recorded when the direction of the waves is 150°. With respect to roll, a similar trend can be seen, where the maximum roll amplitude of 0.425° occurs for a wave heading at 120°. It can also be noted that there exist two resonant frequency regions for the structure in pitch and roll motion. The first resonant frequency occurs at 0.03 Hz which is very close to the natural frequency found previously. The second resonant frequency can be found at approximately 0.1 Hz for both pitch and roll. This frequency coincides with the peak frequency of the wave spectrum indicated in Table 1.

In addition, the results obtained for the coupled motion analysis agree well with the motion performance study on a semi-submersible FOWT undertaken by Zhao, Zhang and Wu [7].

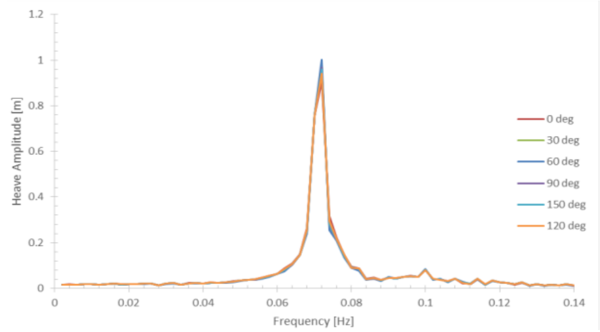


Figure 11. Heave amplitudes in frequency domain for various wave directions

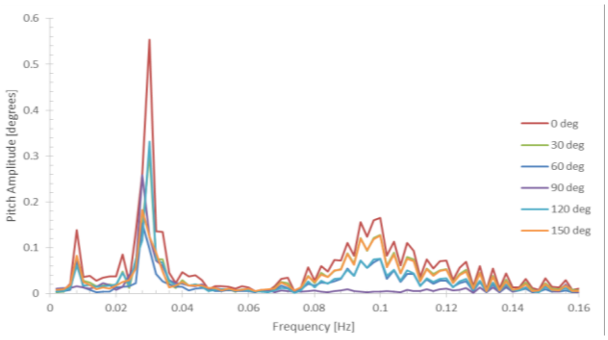


Figure 12. Pitch amplitude s in frequency domain for various wave headings

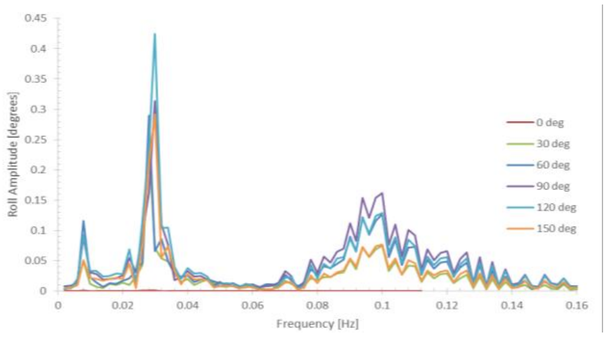


Figure 13. Roll amplitude s in frequency domain for various wave headings

Conclusions

With reference to a 5 MW wind turbine, a conceptual design for a semi-submersible floating wind turbine was developed. Numerical simulations were conducted in frequency and time domains using ANSYS AQWA to analyse the motion response of the structure in wave conditions. The main conclusions from this research are as follows:

- A parametric design study on optimizing the sizes of main column and heave plate successfully established the optimal design of the structure with respect to reduction motions of heave, pitch and roll.
- The response amplitude operators were found to be in good agreement with existing literature.
- The addition of mooring lines to the structure resulted in a phase shift of the natural frequency.
- Results from the time domain simulation in irregular waves showed that the floating wind turbine could be operated safely up to a significant wave height of 4 m.
- This initial investigation provided a basis for further development in the optimisation of the floating wind turbine structure.

Recommendations

Throughout the research, a number of areas were identified where improvements may be made for future research into the motion response of floating wind turbines. Firstly, the gyroscopic loads were neglected because of technical limitations that this force was unable to be modelled in ANSYS AQWA. Secondly, it is recommended that model testing should be conducted so as to confirm the accuracy and validate the numerical simulations.

Furthermore, investigation and comparison between different designs of the FOWT and mooring systems could be conducted to determine the optimal conceptual design for the Bass Strait region.

References

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