Experimental Investigation on a Towing Assessment for a Floating Desalination Plant for Egypt

Islam Amin [1,2], Selda Oterkus [2], Mohamed E.A. Ali[3], Hosam Shawky[3], Erkan Oterkus[2*]

[1] Department of Naval Architecture and Marine Engineering, Port Said University, Egypt
[2] Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, UK;
[3] Egypt Desalination Research Center of Excellence (EDRC) and Hydrogeochemistry Department, Desert Research Centre, Cairo, Egypt;
*Corresponding author: erkan.oterkus@strath.ac.uk; Tel.: +44-141-548-3876

Abstract

Supplying freshwater to remote coastal communities has become challenging due to poor infrastructure and these areas being far from national grids of water in Egypt. A novel FPSO desalination plant powered by on-grid source was proposed to reduce the freshwater shortage in remote coastal cities. The innovative concept has mobility feature to serve different coastal locations depending on seasonal water demand. Since the proposed concept is subjected to wet towing operation to transfer from one site to another, evaluating the motion behaviour during towing operation can improve the reliability of the platform design and reduce the risk during the operation. In this context, the main objective of this study is to experimentally investigate the motion responses of proposed concept in both mooring and towing cases. Furthermore, the calm water resistance at different forward speed and different load conditions were analysed during towing assessment. The results show that variation of peak responses of heave and pitch motions with intensity of towing forward speed may indicate effect of phase lags motion nonlinearity on the overall model response. A clear correlation between towing speed and peak response frequency is demonstrated. The analysed results reproduce the general trends in the observed reduction in the natural frequency and its RAO peak with the towing speed level for different load cases.

Key Words: Cylindrical FPSO; desalination; motion behaviour of offshore vessels; towing operation.

1. Introduction

Demand for freshwater has increased in Egypt due to rapid population growth stresses and limited natural resources. According to recent statistics from the Central Agency for Public Mobilization and Statistics (CAPMAS), population in Egypt exceeded 100 million people. Most of lands in Egypt is desert and more than 94% of the population lives in a small strip of agricultural land along the Nile River and Delta, which represents only about 6% of Egypt's land area. Since Egyptian coastal cities have high potentials to expand and attract more population, this helps the urban growth outside the crowded areas around river Nile and Delta. Coastal areas have mild climate suitable for tourism activities and many oil and gas industries that create attention of investors [1]. However, supply water for these activities are still a key challenge for developing these remote areas. Desalination has now become a viable choice for meeting water demand in growing coastal communities' where there is shortage of water. As a result, the Egyptian government placed a high emphasis on ensuring sustainable water supply management. Under the Egyptian government's strategic plan 2030, the country will have 47 seawater desalination plants [2]. To improve the supply of freshwater to coastal areas, 19 desalination plants will be operated by 2022. Many publications proposed floating desalination plant (FDP) as a solution to overcome water shortage in remote coastal communities instead of land-based plant which need large investment and infrastructure may not be suitable for small scattered remote communities. For example, Chouaki suggested a floating desalination ship powered by liquefied natural gas (LNG) for the Western Mediterranean Sea [3-4]. Fadel also presented a FDP concept powered by fossil fuel and compared it with traditional land-based plants [5]. The paper introduced a fully seagoing desalination vessel called RUMAITH in Abu Dhabi.

Desalination is an energy-intensive process and desalination powered by renewable energy can help to provide clean and sustainable source of power [6]. Marine offshore wind energy is one of the high potential renewable and sustainable energy resources in Egypt, according to the World Bank's report [7]. Egypt has 28 GW of potential for offshore fixed wind turbines, while having huge potential expected to be 208 GW for floating wind turbines along the Gulf of Suez and Red Sea. Some of the biggest challenges that a floating platform supporting an offshore wind turbine faces are the transport and installation stages, since most of floating platforms consequently require additional checks to perform these operations [8]. Recently, a numerical study discussed a novel floating desalination plant powered by a wind turbine which was proposed to overcome the freshwater problem in remote coastal areas [9]. Another on-grid FDP driven by onshore wind farm which is available along Red Sea coastline was developed by Amin et al. [10]. Based on hydrodynamic performance investigation, the proposed FDP platform was selected as cylindrical configuration and consists of a floater, desalination units and power driver [11, 12].

Since the proposed concepts are subjected to wet towing operation to transfer from one site to another, evaluating the motion behaviour during towing operation is important task for reliability and the safety of the platform design. Many publications discussed the offshore transportation technology to understand the performance of motion responses during towing operation. Tank model tests of iceberg towing in open water and in sea ice have been carried out by Kenneth and Aleksey [13]. The motion performance of a barge equipped with a rectangular tank has been investigated experimentally in both dry and sloshing conditions [14]. Due to liquid sloshing the study concluded some changes in RAO responses. Field experiments on wet towing of an integrated transportation and installation vessel with two bucket foundations for offshore wind turbines was investigated [15]. The motion behaviour results show that the dedicated vessel is quite stable during wet towing. Numerical analysis of offshore integrated meteorological mast for wind farms during wet towing transportation was investigated in order to find out the towing dynamic behaviours of the proposed system with different drafts and towing velocities. Draft depths impact more on pitch motion than on heave motion [16]. Towing speed effect on dynamic stability of one-step integrated wind turbine transportation vessel was numerically investigated [17]. The study shows that reducing draft, increasing speed and increasing wave height will reduce the towing stability. Interesting investigation of rudder shaped-like offshore hull configuration was performed in order to minimize the drag force during towing by using the resistance model test [18].

Although the wave frequency variation influences the floater motion at zero speed, the effect of the frequency change due to floater moving through the waves is much more pronounced. Therefore, evaluating the motion behaviour of a novel FDP concept during towing operation provides an important information for better understanding of how the forward speed influences the floater motion which can improve the reliability of the design and reduce the risk during the operation. In this study, the towing assessment of the FDP model is experimentally investigated when it is being towed within the environment loads of deployment area in Egypt. For this purpose, FDP model is tested at different towing speed and different load cases with the aim of determining and evaluating the motion behaviour and resistance force.

2. Proposed FDP concept

a. General description of FDP

The proposed concept is a floating FPSO platform supporting a desalinated water production system, storage water system, and offload system to transfer the freshwater to the shore. The plant is driven by onshore wind turbines and on deck solar power system, as shown in Figure 1. The outer diameter of the main hull is 70 m and the depth is 32 m. The upper deck diameter is extended to 87.5 m to increase the solar panels' installation area. The heave plate was fitted to the bottom of the hull with a diameter of 87.5 m and a thickness of 2.5 m. Six RO units, each with 2000 m^3/day capacity, were designed in a novel circular arrangement to reduce the piping system. The total production of the plant is 10,000 m^3/day. The central seawater feeding tank for all RO units is used and connected by feeding pipelines. The plant is arranged to place solar panels on the top floor, the RO units and other desalination equipment on the operation deck, and the freshwater storage and ballast tanks in the lower partitions as shown in Figure 1.

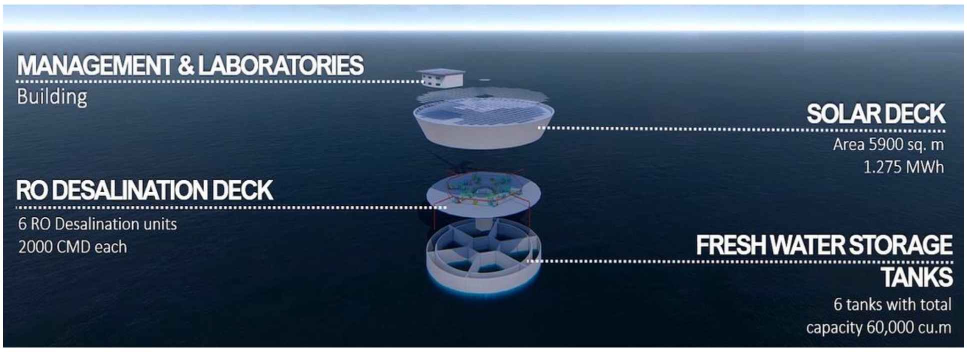


Figure 1: Proposed floating desalination plant concept [10].

b. FDP mobility feature

Although the land-based plants offer many opportunities, such as mass production, stability in supplement, and less risk in operation, the installation and capital costs are still incomparable with mobile plants for small and remote communities. In addition, floating desalination plants generally offer environmental benefits compared with land-based designs because of the safe removal of brine far from the coastal marine environment with no additional cost. Motivated by eliminating the infrastructure cost, mobile floating platforms could open the way for an on-grid desalination plant powered by energy harvesting from offshore wind sources. Therefore, a mobile desalination plant is proposed to serve the coastlines of this area to reduce the overhead, installation, and operation costs for low and medium water demands.

Egyptian east coastline is considered as a remote area far from Nile and Delta but has a high potential to attract population and establish new societies outside the crowded areas of Egypt. For a long time, this area attracted only tourism and oil industries without urban background. Populations in these remote areas without water or electricity grids eliminate any governmental efforts to develop this area. Amin et al. [9] previously proposed mobile off-grid FDP plants driven by wind power. Same FDP platform was proposed in on-grid mode driven by onshore wind power supply which is available along Red Sea coastline [10]. The concept was proposed for the development of small and remote coastal communities with small and medium water demands. A cylindrical platform was selected with mobile feature which can be towed between coastal cities depending on water demands. The proposed concept can eliminate the infrastructure cost compared with land-based plant, is suitable for treating with sessional demands in some areas and does not need for large land area. Offshore mobile plants can also encourage marine renewable sector by offering off-grid or on-grid desalination plants powered by energy harvesting from onshore or offshore wind sources.

Figure 2: Proposed FDP concept.

c. ***Deployment area and environmental loads***

The deployment area in the Red Sea has moderate sea state. Determination of wave spectrum of the deployment area is a very important task in order to avoid frequency matching between the wave exciting frequency and the natural frequency of FDP platform.

Based on the DNV-GL classification [19], wind speed parameter can be used to calculate the wave spectrum in the deployment area, as shown in Equations (1) and (2).

$$S_{PM}(\omega) = \frac{\alpha . g^2}{\omega^5} . exp\left[-\beta\left(\frac{g}{U.\omega}\right)^{-4}\right], \tag{1}$$

$$\omega = 2\pi f, \tag{2}$$

where $\alpha = 8.1 * 10^{-3}$,

$\beta = 0.74$,

$g = 9.81$ m/sec^2, and

$U$is the wind speed in m/s.

According to wind statistics in the Red Sea, the average range of wind speed was selected for 9 m/s to 14 m/s. The wave spectrum curve for each wind speed are plotted and its peak is highlighted with dashed line as shown in Figure 3.

Moreover, based on the recorded wave heights and periods in the Red Sea area, the significant wave height and wave period were found at 2.15 m and 8 s, respectively [20]. The wave spectrum was calculated based on this data and plotted as dashed black curve in Figure 3. According to the spectrum results, the wave bands in the Red Sea area are from 0.6 to 1 rad/s, and the proposed plant motion responses should be out of this range to be safe when in operation.

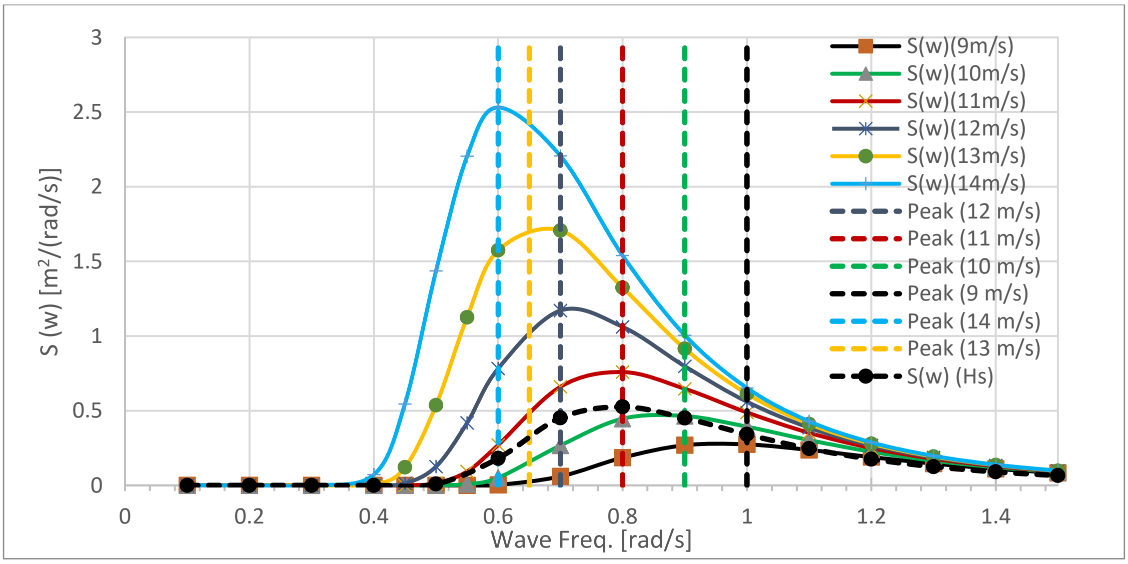


Figure 3: Wave spectrum of Red Sea.

d. ***Motion behaviour criteria and assumptions***

FDP unit was designed to serve coastal cities based on their freshwater demands. The platform was designed to be towed by tugs. Motion responses during the towing is one of challenges that such kind of mobile units face.

Based on GL motion criteria, in case of transportation in weather restricted operation in benign areas, the single amplitude of roll and pitch motion should be lower than 5 degrees [21]. Moreover, the design wave height for towing operation shall be the significant wave height (Hs) in the deployment area. The design wind speed shall be the 1-minute mean velocity at a reference height of 10 m above sea level.

For unmoored mode, the heave, pitch and roll responses are resonant motions, while the sway, surge and yaw are not due to absent of stiffness in the latter motions [22]. Due to symmetric shape of FDP, consideration should be given to the heave and pitch responses. DNV recommends to carefully select the suitable period for towing and consider the typical weather condition in towing route [23].

3. Experimental test

Experimental tests during towing in wave environment are important tools for the development of mobile floating plants and other similar hybrid systems. The present experiments can help the designers to ensure the unit's motion performance at the early design stages, especially for such novel concept.

a. Model test set-up

A cylindrical floating platform representing FDP concept was experimentally tested in this study. The model tests were conducted with a geometrical scaling 1:100 (scale factor λ = 100), at the University of Strathclyde's Kelvin Hydrodynamics Laboratory. The tank has a total length of 76 m, a width of 4.6 m, and a water depth of 1.91 m. The tank was provided with a carriage that had an electronic control system that could operate and obtain the desired data. The model was placed at state point far from the towing tank edge with 10 m in each running case. The model towed with a tow rope made of Dyneema. The tension in the rowing line was recorded using a load cell connected with the end of towing line and fixed on the carriage. The carriage can perform running speed up to 4 m/sec. The tank profile and experimental set up are shown in Figure 4.

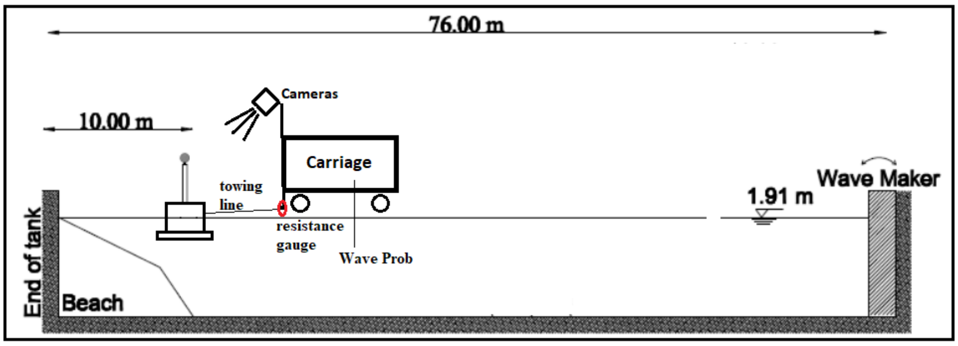


Figure 4: Tank profile and experimental setup.

A wave maker was placed at the end of the tank creating regular sinusoidal waves. Moreover, the tank had absorption facilities to remove the effect of reflected waves. The wave profile was monitored and captured using ultrasonic wave probe fixed on the carriage as shown in Figure 4.

The motion of the model was traced by four 6-DOF QUALISYS motion camera system fitted at the end of the carriage as shown in Figure 5. The model was fitted with four illuminated balls of infrared reflectors attached at the top of the model tower. The four cameras located above the carriage adjusted the coordinates of the reflectors in the model space. Then, corrected reflector coordinates to the platform's vertical center of gravity (VCG) defined the test origin. The model motion was detected with a body-fixed coordinate system, and three motions were calculated and recorded in real time through Spike2 V9.06 data converter.

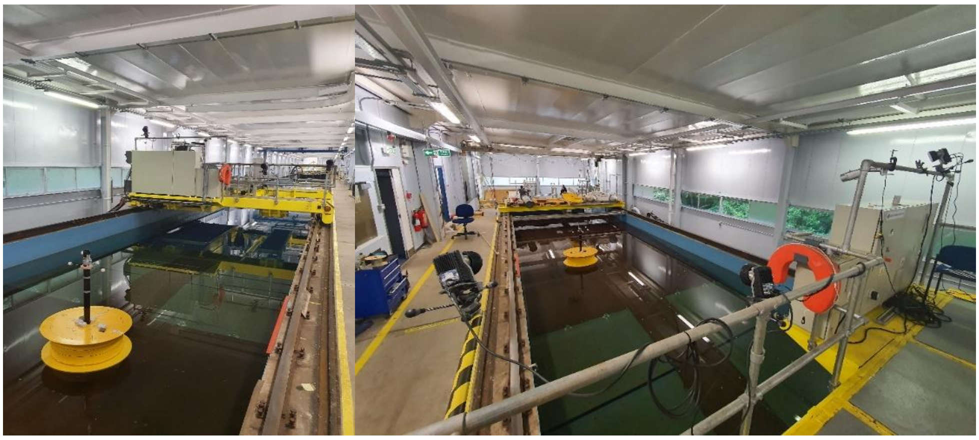


Figure 5: Qualisys camera system attached in the carriage and the model towed by wire at the back of carriage.

b. *Model characteristic*

The FDP cylindrical model has an outer diameter of 0.7 m and a depth of 0.32 m. In order to increase the deck area, the upper deck diameter was extended to 0.875 m. Model bottom diameter was also extended by fitting a heave plate to damp the vertical motion. The heave plate has a diameter of 0.875 m and a thickness of 0.025 m. The cylindrical model was manufactured at the technical workshop of the Kelvin Hydrodynamics Laboratory at the University of Strathclyde in the United Kingdom. The model was built from foam and fiberglass, while wood was used for the upper deck, lower bottom, and heave plate. The model is shown in Figure 6.

Table 1. FDP properties and main dimensions.

Parameters	Unit	Full scale	Scaled (λ=1/100)
Upper deck diameter	m	87.5	0.875
Main platform diameter	m	70	0.7
Heave plate diameter	m	87.5	0.875
Platform depth	m	32	0.32
Turbine tower height	m	84	0.84
Draft (Ballast cond.)	m	14.4	0.144
Draft (Light-ship cond.)	m	5.25	0.0525
Displacement (Ballast cond.)	ton	62680	0.06115
Displacement (Light-ship cond.)	ton	25625	0.025
VCG of Ballast condition	m	13.89	0.1389
VCG of Light-ship condition	m	18.99	0.1899
Towing speed range	m/s	2 to 4	0.2 to 0.4

The plant has three load-case conditions; namely, lightship, ballast, and full-load conditions were described in detail in a previous experimental study [10]. In mobility mode, the plant can be towed in lightship and ballast conditions, on which the present study focused to investigate the motion responses.

Figure 6: Model on the swinging table.

c. ***Test matrix***

In the present model test, the test matrix was divided to three test groups as follows:

1. Based case at zero forward speed (moored case).
2. Tests where the model was subjected to a change in towing forward speed.
3. Tests where the model was subjected to a change in loading condition.

The test was conducted in regular waves. The test matrix is presented in Table 2.

Table 2: Test Matrix.

Test number	Description	Load condition	Towing Speed [m/s]	Range of Frequency [Hz]
1	Calm Water Resistance	Lightship	From 0.2 to 0.6	Calm water
2		Ballast	From 0.2 to 0.6	
3	Moored	Lightship	0	0.2 to 1
4		Ballast	0	
5	Towed	Lightship	2	
			3	
			4	
6		Ballast	2	
			3	
			4	

4. Experimental Motion responses

Since the model natural frequency has the largest impact on the motion responses, the effect of towing speed and load condition during towing on the peak responses were investigated using experimental testing approach in frequency domain and time domain. Understanding the motion behaviour of the proposed FDP concept during towing operation in its deployment area is beneficial to the design of such concepts and its safety. The motion responses of the FDP model during towing operation was evaluated in the present experiments in lightship and ballast load cases. The platform's heave and pitch responses were experimentally measured in a range of wave frequencies matching with wave band range of Red Sea deployment area.

a. *Calm Water Resistance*

The towing resistance was obtained experimentally at two different load conditions. The model was tested for a speed range of 0.2 to 0.6 m/s (equal to 2 to 6 m/s for full-scale). The model towing was performed in calm water condition. The model test results are shown in Figure 7. The towing resistance is compared between light-ship (surface towing) at 5.25 m and ballast conditions at 14.4 m (submerged towing). The wind and current loads were neglected in this study. Due to increase in the wetted area in the ballast case with respect to the light-ship case, the resistance force increased dramatically with increase in the towing speed.

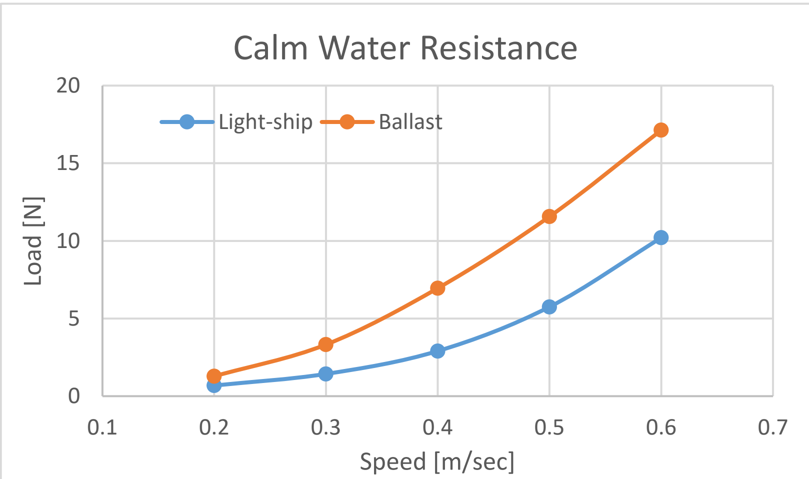
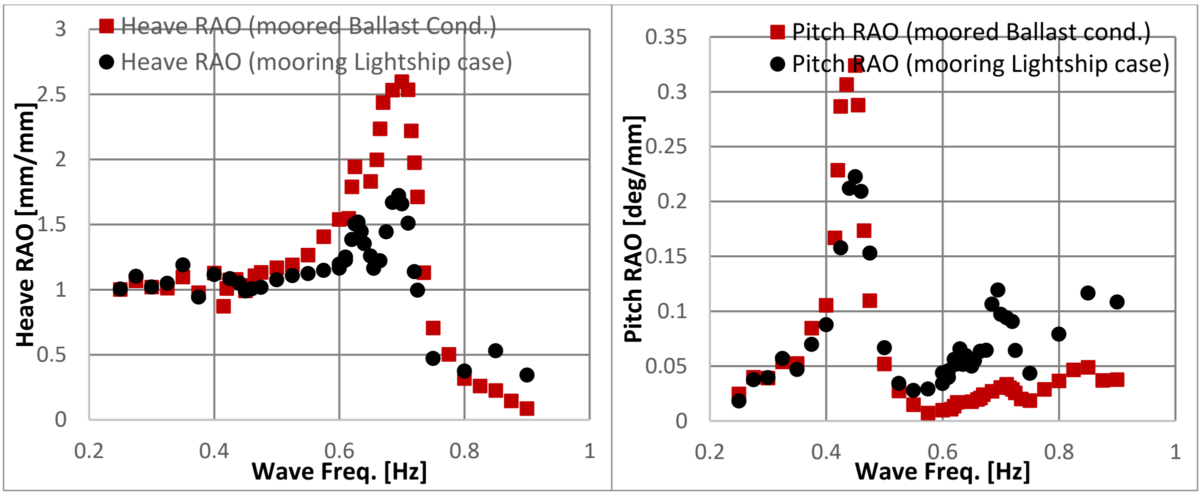


Figure 7: Calm water resistance at different load conditions.

b. *Based Case (Moored FDP responses)*

In order to evaluate the motion responses of the FDP during towing operation, the motion performance at zero forward speed condition (moored case) was analysed and set as based case for the present study. At zero speed, the effect of changing the load condition from light-ship to ballast case does not significantly affect the pitch peak response frequency in both heave and pitch RAOs as shown in Figure 8 (a) and (b) (stay around 0.7 rad/s in case of pitch motion and 0.45 rad/s in case of pitch motion). A slight secondary peak can be observed near the heave natural frequency (0.7 rad/s) in pitch RAOs for both loading scenarios. The secondary peak height increases slightly in light-ship load case as shown in Figures 8 (b). In the light-ship condition as shown in Figure 8 (a), it is interesting to note that the heave natural range contains two peaks which looks like a V shape curve. Increase in heave and pitch RAO values are expected due to increase in floater total displacement which consequently effect the model moment of inertia.

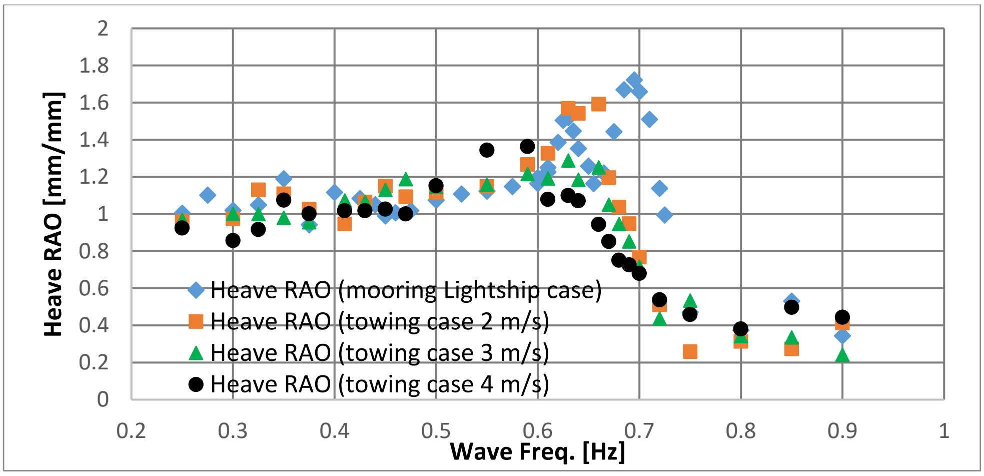


a) Heave RAO b) Pitch RAO

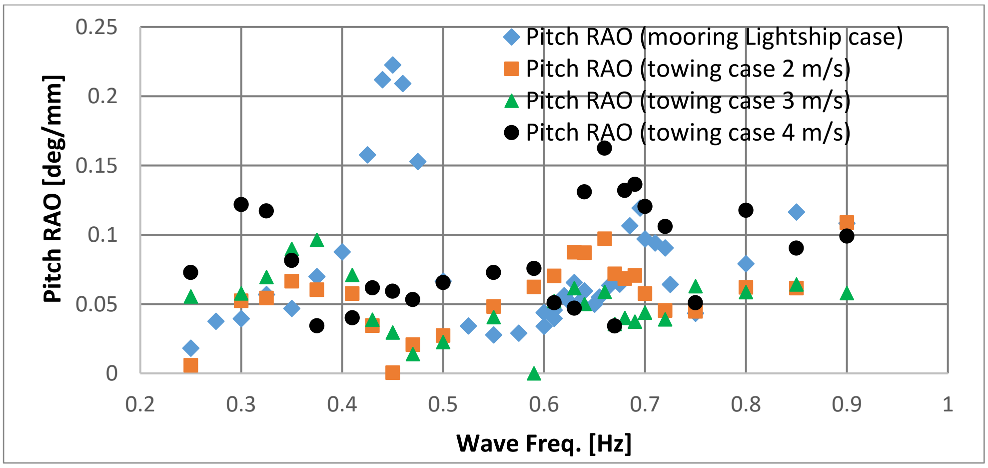
Figure 8: Heave and pitch motion responses at zero towing speed for different load conditions.

c. *Effect of towing speed on motion behaviour of FDP*

The relation among towing forward speed and motion responses are analyzed in this section. The heave and pitch motion responses for different towing speeds are compared in a frequency domain in light-ship condition as shown in Figure 9 (a) and (b). The damped natural frequency decreases in both heave and pitch responses with respect to the mooring case (zero forward speed). The same observation occurs in the towing in ballast condition where the heave and pitch motions' peak frequency also decreases with respect to the moored case as shown in Figure 10 (a) and (b). In the heave response, it can be observed that the influence of towing forward speed is very significant on the natural frequency of the model. However, for the remaining wave frequency ranges, there is no significant change in heave RAO results. In pitch responses, the effect of towing forward speed on RAO is more evident and remarkable for all wave frequency ranges rather than in the heave responses as shown in Figure 9 (b) and Figure 10 (b). However, when the forward towing speed increases, the scattered waves could travel ahead of the model which lead to change the traditional wave radiation condition. The new wave radiation condition could lead to change the motion responses behaviors especially at natural frequency ranges.

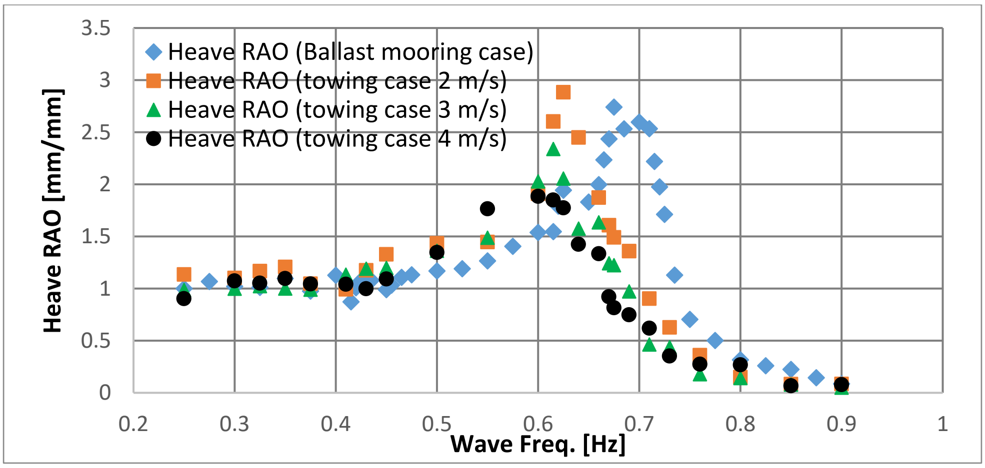


a) Heave RAO

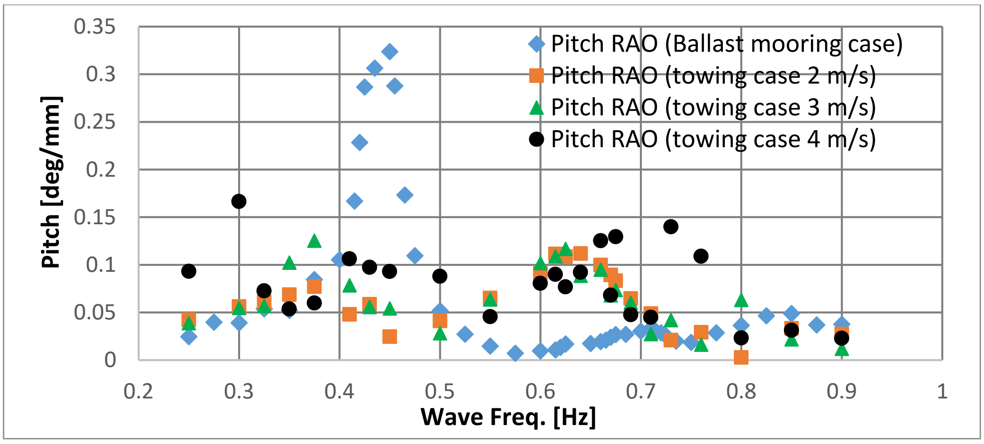


b) Pitch RAO

Figure 9: Comparison of (a) heave RAO and (b) pitch RAO for FDP model in different towing speeds for light-ship load condition.



a) Heave RAO



b) Pitch RAO

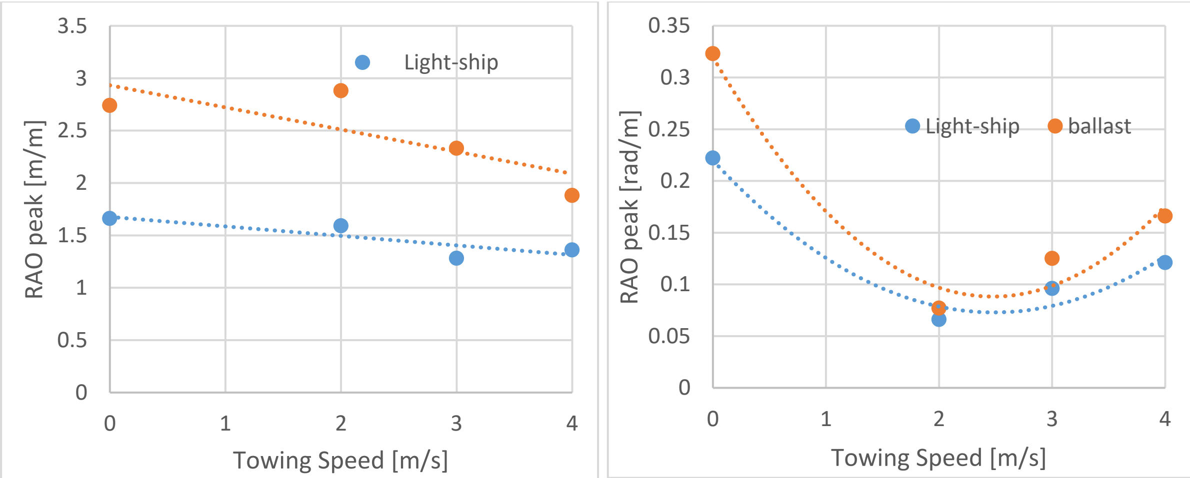
Figure 10: Comparison of (a) heave RAO and (b) pitch RAO for FDP model in different towing speeds for ballast load condition.

In the natural frequency range, it can be noticed that the heave and pitch peaks have a relationship with towing forward speed. The heave and pitch peak responses are damped or decrease with the increasing towing forward speed, as shown in Figure 9 and Figure 10. While in pitch secondary peak responses, the responses increase when the towing speed increases, as shown in Figure 9 (b) and Figure 10 (b).

Table 3: Comparison of heave and pitch RAO first peaks for different towing forward speeds and their decrease in percentages with respect to moored case.

Towing speed	Light-ship		Ballast		Decrease % (Light-ship)		Decrease % (Ballast)	
	Heave	Pitch	Heave	Pitch	Heave	Pitch	Heave	Pitch
0	1.66	0.222	2.74	0.323	-	-	-	-
2	1.59	0.066	2.88	0.077	4.216	70.27	-5.10	76.16099
3	1.28	0.096	2.33	0.125	22.89	56.75	14.96	61.30031
4	1.36	0.121	1.88	0.166	18.07	45.49	31.38	48.60681

To evaluate the effect of towing speed on RAO peak responses of the FDP model, two comparisons were considered in Figures 11 and 12. The relationship between the measured heave and pitch RAO peaks and towing forward speed for different two load conditions are shown in Figures 11 (a) and (b) and Table 3. The RAO peaks decrease in heave responses for light-ship load condition up to 18 % with respect to the mooring case, while in ballast load condition they decrease up to 31% as shown in Table 3. For ballast case at 2 m/s forward towing speed, the heave peak increased 5% with respect to the mooring case while all other cases (5 towing cases) the heave peaks decreased as shown in Figure 11 (a). For the towing case, all pitch RAO peaks were observed to be lower than the moored case. The peak values decreased until lowest point and then increased slightly again when the towing speed was increased as shown in Figure 11 (b). More test cases are recommended to investigate this behavior in a further study. The same observation occurs in the heave damped natural frequency responses where the damped natural frequencies also decrease about 15% in both load conditions with respect to the moored case as shown in Table 3. In the pitch response, it can be observed that the influence of towing forward speed is very significant in decreasing the natural frequency (up to 33%) and the RAO (up to 76%) of the model with respect to the moored case. Therefore, it can be concluded that the influence of the towing forward speed on the motion responses of the FDP model is positive regarding to the first natural frequency responses and more significant in pitch responses. While for the pitch motion, the influence is negative at secondary peak responses and cannot be considered marginal due to its location near to the wave natural excitation frequency in the deployment area.

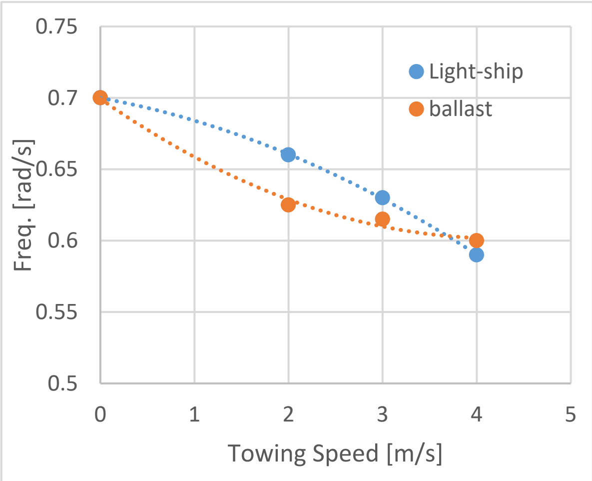


a) Heave responses b) Pitch responses

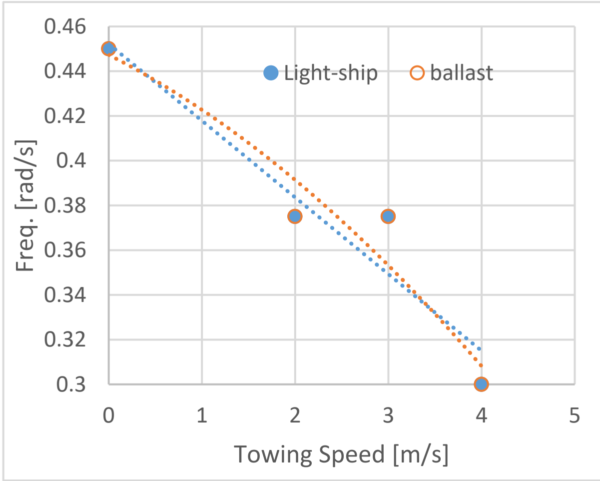
Figure 11: The relationship between RAO peaks responses and towing forward speed at different load conditions.

Table 4: Comparison of heave and pitch peak frequencies for different towing forward speeds and their decrease in percentages with respect to moored case.

Towing speed	Light-ship		Ballast		Decrease % (Light-ship)		Decrease % (Ballast)	
	Heave	Pitch	Heave	Pitch	Heave	Pitch	Heave	Pitch
0	0.7	0.45	0.7	0.45	-	-	-	-
2	0.66	0.375	0.625	0.375	5.71	16.66	10.71429	16.66
3	0.63	0.375	0.615	0.375	10	22.22	12.14286	16.66
4	0.59	0.3	0.6	0.3	15.71	33.33	14.28571	33.33



a) Heave responses



b) Pitch responses

Figure 12: The relationship between heave and pitch peak frequencies and towing forward speed at different load conditions.

In the pitch RAO responses for both load conditions, it can be observed that small secondary peak occurs near heave natural frequency (0.7 rad/s). In light-ship load case, the secondary peak RAO value decreases slightly with increase in the towing forward speed except at4 m/s as shown in Figures 9 (b). In the ballast load case as shown in Figure 10 (b), it is interesting to note that the secondary peak sharply increases with increase in towing speed for all towing speeds up to three times with respect to moored case as shown in Table 5. The relationship between pitch secondary peak frequencies and towing forward speed at different load conditions is presented in Figure 13.

Table 5: Comparison of pitch secondary peak frequencies for different towing forward speeds and their increase in percentages with respect to moored case.

Speed	Light-ship	Ballast	Increases % (Light-ship)	Increases % (Ballast)
0	0.12	0.03	-	-
2	0.097	0.1116	-19.16667	272
3	0.061	0.118	-49.16667	293.333
4	0.162	0.14	35	366.667

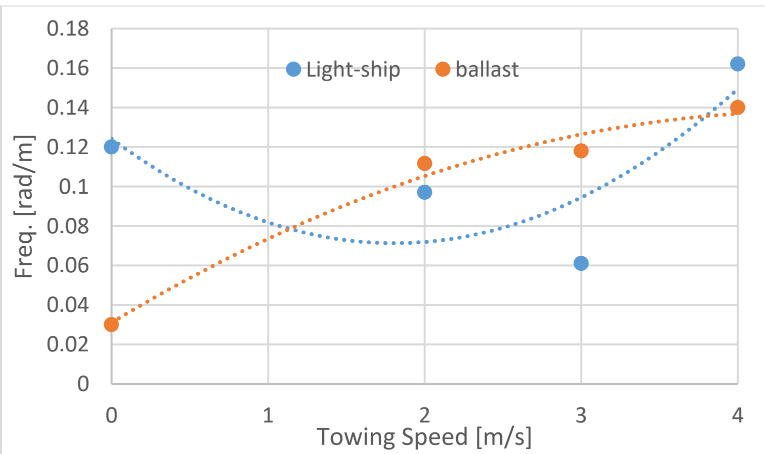
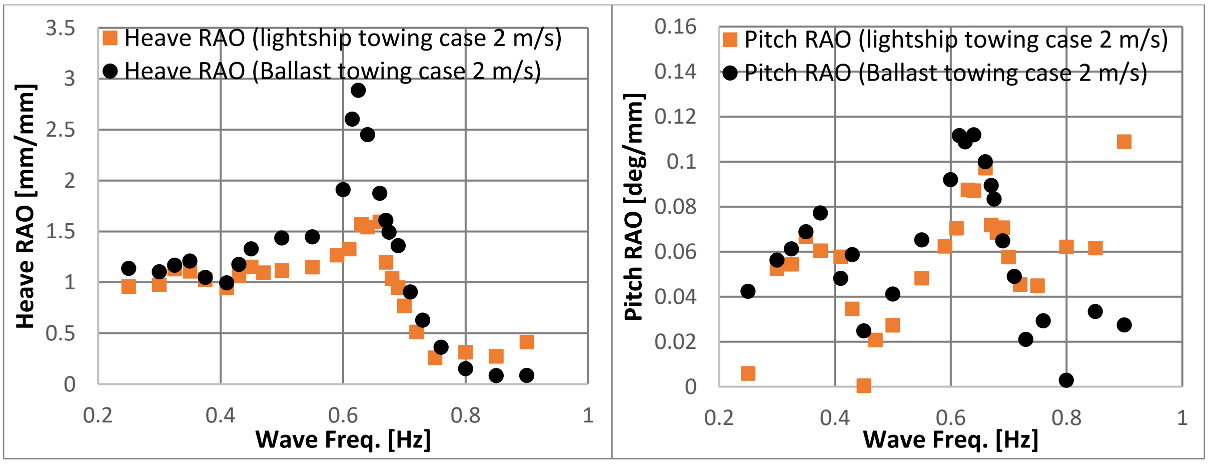


Figure 13: The relationship between pitch secondary peak frequencies and towing forward speeds at different load conditions.

d. Effect of Load Conditions on Motion Behaviour of FDP

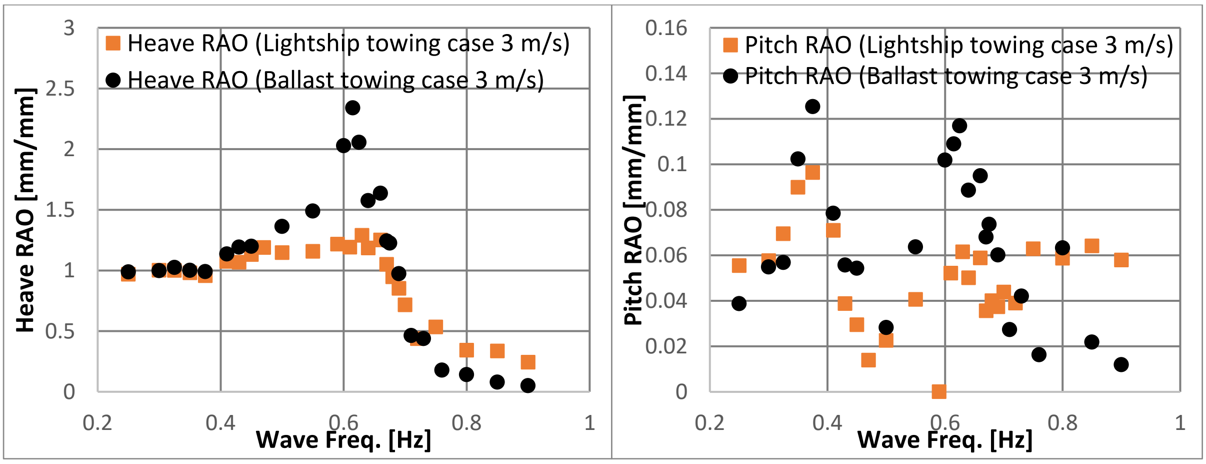
A comparison of two load cases, namely light-ship and ballast load cases, was analyzed in order to understand the effect of change in load conditions during the towing operation on the heave and pitch motions. The heave and pitch RAOs obtained for the FDP model at different towing forward speeds for load conditions as shown in Figure 14, 15 and 16. It can be revealed that the effect of load condition changes does not significantly affect the pitch response frequency at towing forward speed of 2 m/s as shown in Figure 14 (b). The pitch responses increase at ballast load cases with respect to light-ship case at towing forward speeds of 3 m/s and 4 m/s. While, it is observed that the influence of load condition on the heave motion responses of the FDP model is very significant especially at natural frequency with respect to light-ship case as shown in Figure 14 (a), Figure 15 (a) and Figure 16 (a).

It should be noticed that the reasons behind the increase in the heave motion in the case of the ballast case with respect to the light-ship case is due to the increase in added mass with effect on the damping coefficient.



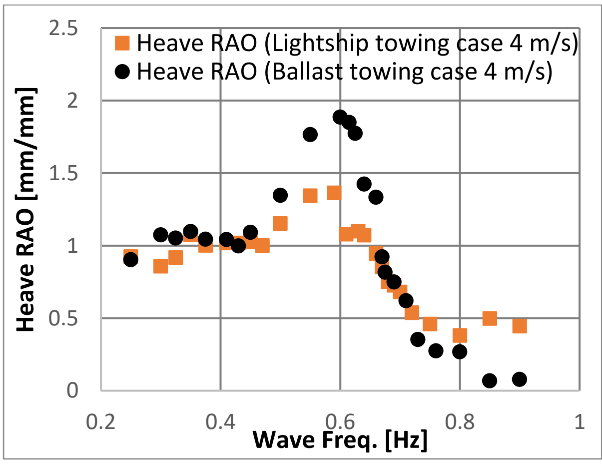
a) Heave RAO b) Pitch RAO

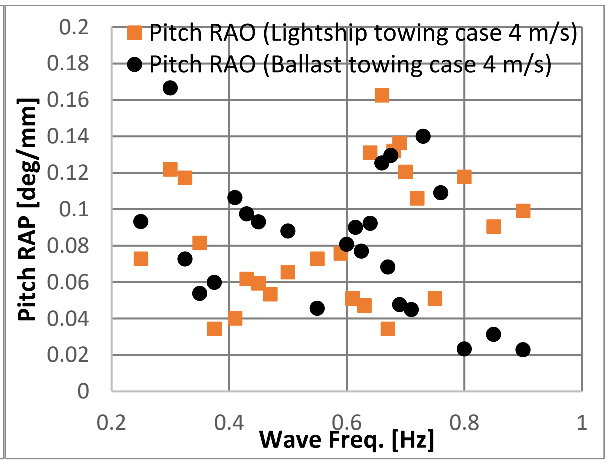
Figure 14: Comparison of (a) heave RAO and (b) pitch RAO for FDP model in towing cases at forward speed of 2 m/s for different load condition.



a) Heave RAO b) Pitch RAO

Figure 15: Comparison of (a) heave RAO and (b) pitch RAO for FDP model in towing cases at forward speed of 3 m/s for different load condition.





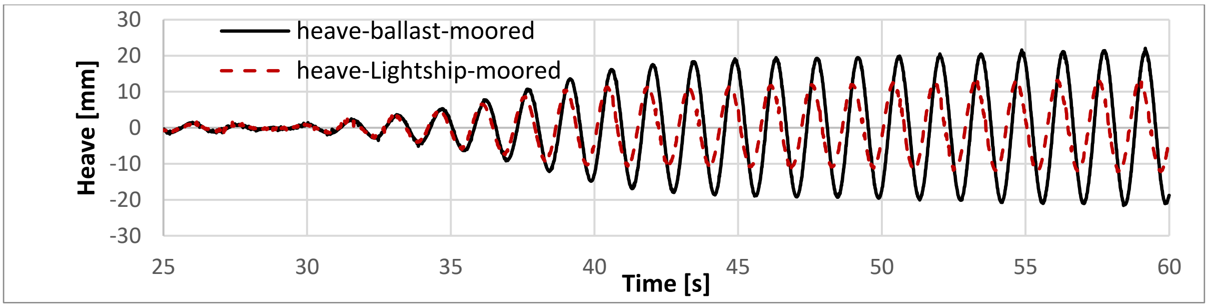
a) Heave RAO b) Pitch RAO

Figure 16: Comparison of (a) heave RAO and (b) pitch RAO for FDP model in towing cases at forward speed of 4 m/s for different load condition.

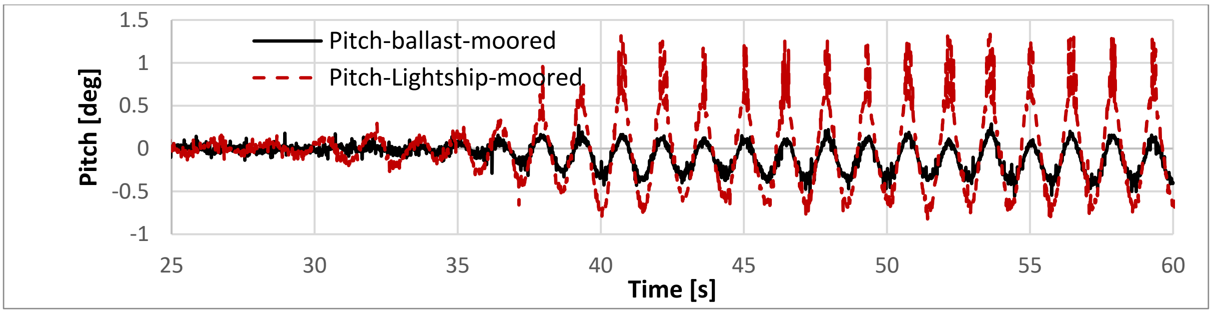
e. *Time domain behaviour of towing speed on motion behaviour of FDP*

Another approach to study the effect of load condition and towing forward speed on the overall motion responses of FDP concept is to evaluate the heave and pitch motions at the peak frequency with time history.

The time series of the heave response of the FDP model for both light-ship and ballast cases at zero towing speed and wave frequency of 0.7 rad/s (response peak) are shown in Figure 17. It is important to notice that the heave responses in case of ballast condition are higher than light-ship case. While in pitch responses, heave responses are higher for the light-ship case (secondary pitch peak). The aim of the present comparison is to show the effect of load conditions on the heave and pitch motions of the FDP. The increment in the heave motion time series in the ballast case compared to the light-ship case caused due to the increase in added mass value with effect on the damping coefficient.



a) Heave responses.



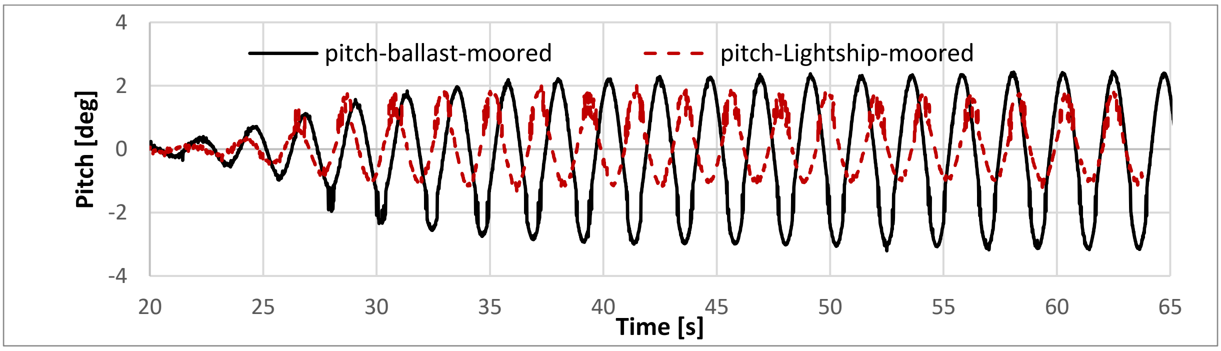
b) Pitch responses

Figure 17: Heave and pitch time history of FDP model at 0.7 rad/s at zero towing speed for ballast and light-ship load cases.

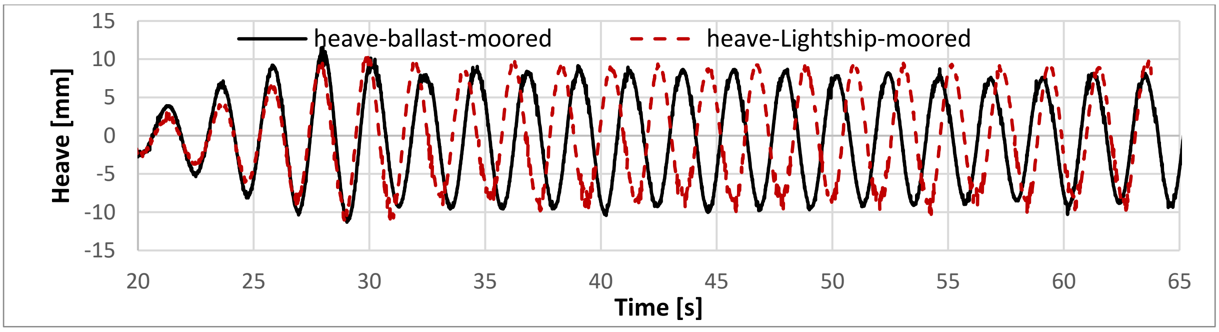
The same observation occurs at wave frequency of 0.45 rad/s (pitch natural frequency) where the heave responses in ballast case are higher than the light-ship case as shown in Figure 18 (a). In the pitch response, it can be observed that the influence of load condition is not significant as shown in Figure 18(b).

However, for the towing speed range at heave natural frequency range, there is a significant change in pitch responses results (secondary peak). The pitch response increases with the increase in towing forward speed as shown in Figure 19 (a). The pitch responses at towing forward speed of 4 m/s exceed 5 degrees. Also, in pitch natural frequency (0.45 rad/s), the pitch responses increase when the towing speed increases as shown in Figure 20 (a). While in heave responses, the effect of towing forward speed on heave responses is d more evident and remarkable for ballast load case with respect to light-ship case as shown in Figure 19 (b) and Figure 20 (b).

It is interesting to note that the pitch response is symmetric around its rotational axis at zero towing speed. While in towing cases, pitch response sharply increases in model forepeak and decrease in model aft peak as shown in Figure 19 (a) and Figure 20 (a). The same observation occurs at heave response where the heave responses' symmetry disappears with increasing the forward towing speed as shown in Figures 19 (b) and 20 (b).

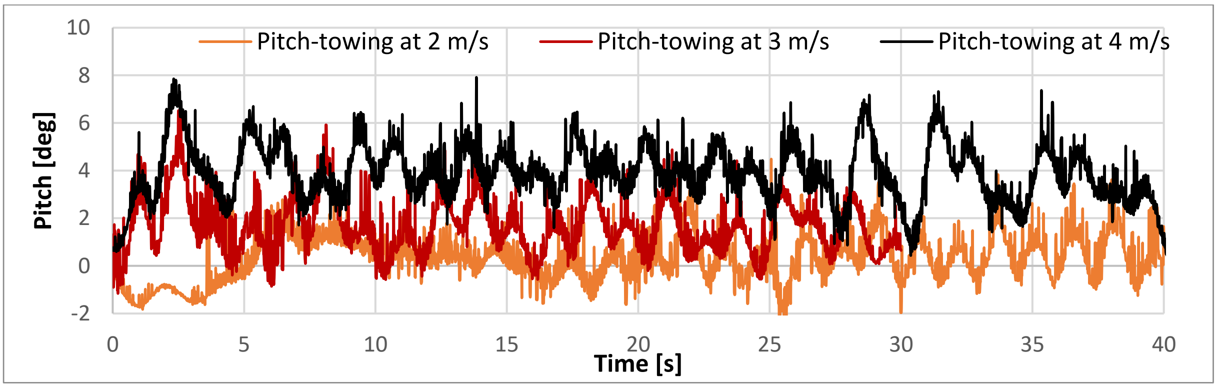


a) Heave responses.

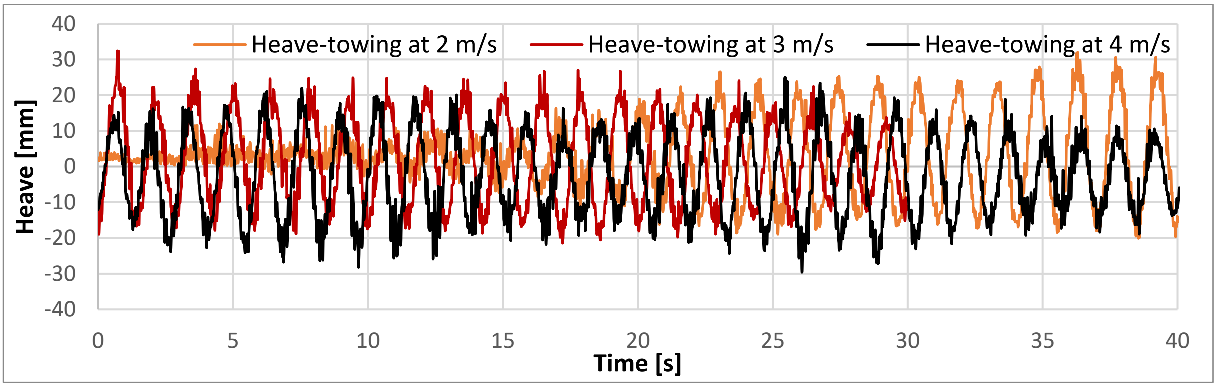


b) Pitch responses

Figure 18: Heave and pitch time history of FDP model at 0.45 Hz and zero towing speed for ballast and light-ship load cases.

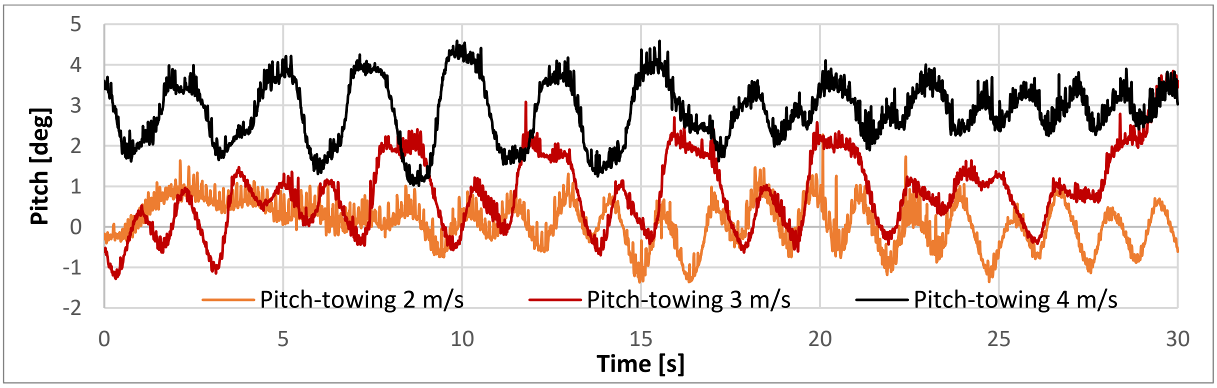


a) Heave responses

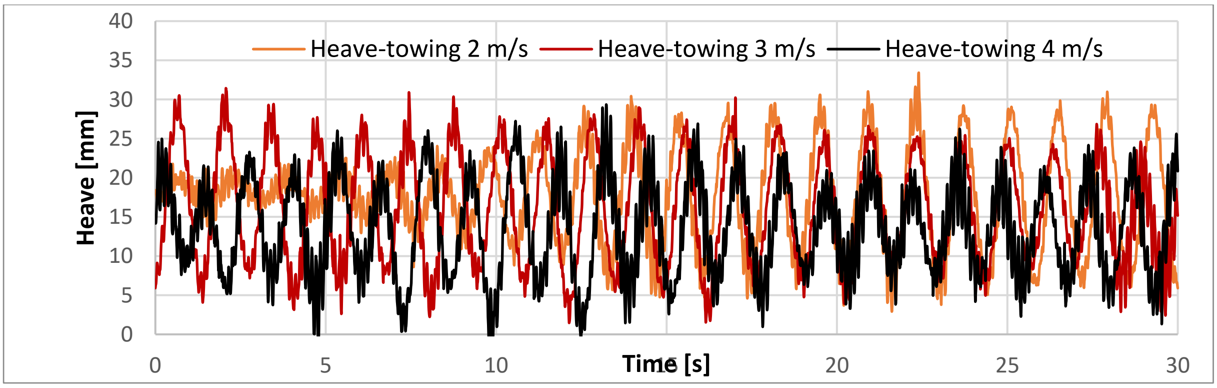


b) Pitch responses

Figure 19: Heave and pitch time history of FDP model at 0.7 Hz and different towing speed for ballast load cases.



a) Heave responses

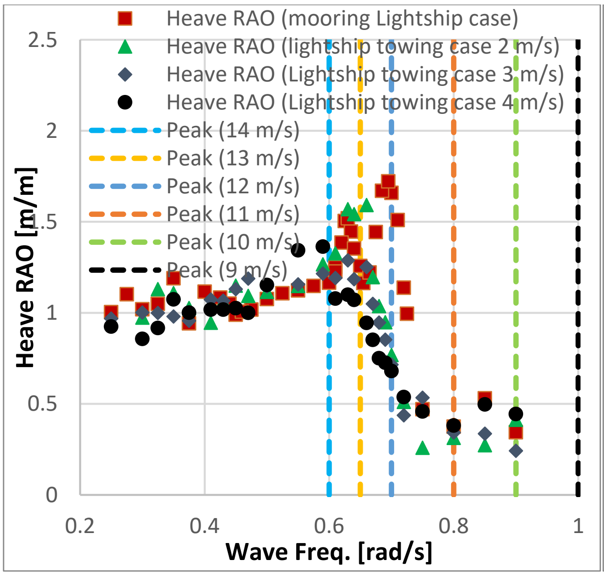


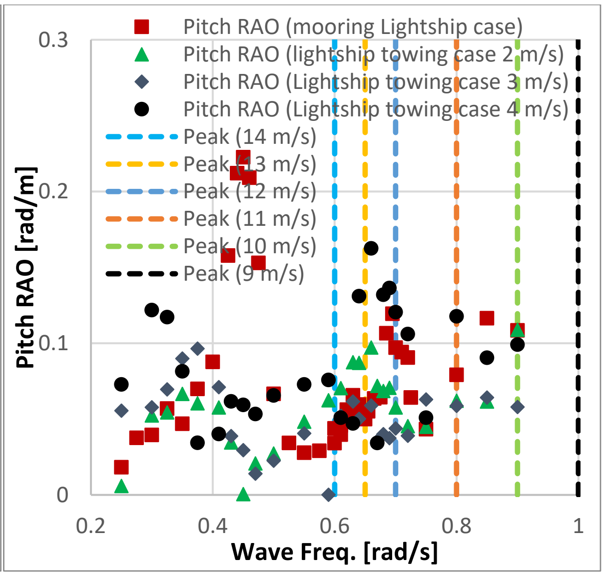
b) Pitch responses

Figure 20: Heave and pitch time history of FDP model at 0.7 Hz and different towing speed for light-ship load cases.

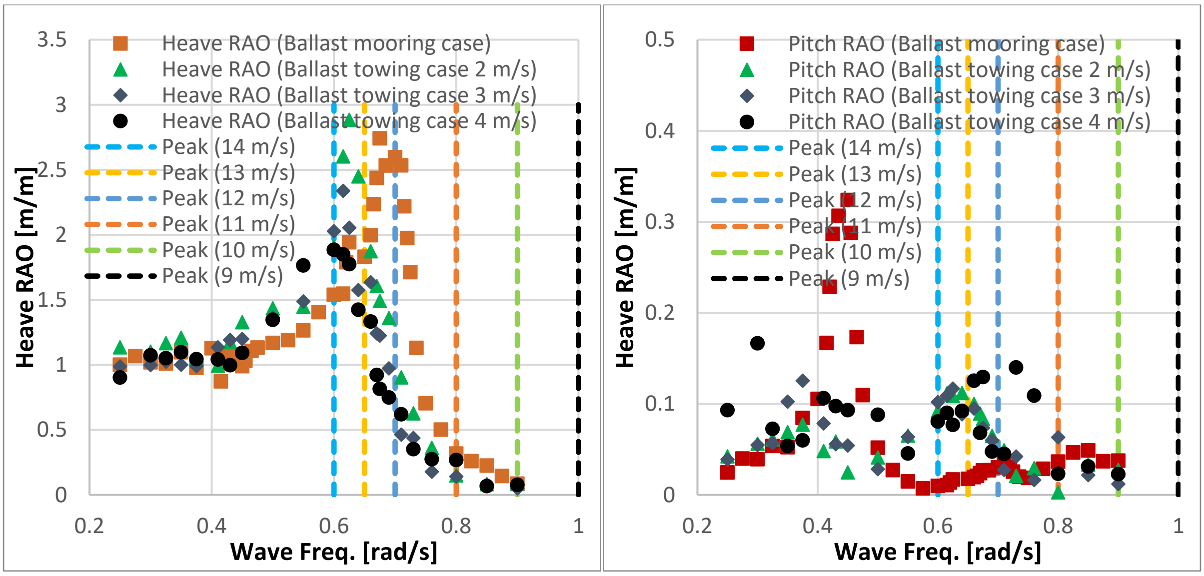
f. Suitability of Towing Operation for Red Sea Area

As previously stated, the heave and pitch motions are resonant motions. If the wave exciting frequency matches with the natural frequency of the FDP then resonance would occur. In order to evaluate the suitability of FDP model for Red Sea deployment area, heave and pitch motion responses were compared with wave excitation spectrum peaks at different wind speeds in Red Sea area as shown in Figure 21. Based on responses results and wave spectrum analysis, the maximum wind speed suitable for towing operation is 11 m/s in order to avoid the wave excitation forces in this area.





a) Heave response for light-ship case. b) Pitch response for light-ship case.



c) Heave response for ballast case. d) Pitch response for ballast case.

Figure 21: Heave and pitch RAO and wave spectrum peaks at different wind speeds for FDP model at different towing speeds for different load cases.

Conclusion

Evaluation of the motion behaviour for a novel FDP concept during its towing operation is an important information for better understanding of how the forward speed and load condition influence the floater motion which can improve the reliability of the design and reduce the risk during the operation. The motion responses and calm water resistance are determined using experimental test in different towing speed and load conditions in this study. A clear correlation is demonstrated between towing speed and the peak RAO response value and frequency. Compared to zero towing speed (moored case), the towing at light-ship load condition gives better motion responses and less resistance value. From motion responses during towing in light-ship condition, the peak responses of heave RAO decrease with increase in towing forward speed.

Although the wave frequency variation influences the floater motion at zero speed, the effect of the frequency change due to floater moving through the waves is much more pronounced. The heave and pitch motion behaviour of a model progressing through a following wave with the towing speed in relation to the load condition will be influenced especially near natural frequencies.

The experiment results show that the forward speed-motion responses interaction effects during towing can reduce the fundamental heave natural frequency and its RAO peak of the model with more than 18% in case of light-ship load condition and 31% in ballast case. The same observation occurs in the pitch natural frequency responses where the damped natural frequencies also decrease about 33% and the RAO peak 76% with respect to the moored case. For the pitch secondary peak, the RAO sharply increases with increase in towing speed for all towing speeds up to three times with respect to moored case. Therefore, it can be concluded that the influence of the towing forward speed on the motion responses of the FDP model is positive regarding to first natural frequency responses and more significant in pitch responses. While for pitch motion, the influence is negative at secondary peak responses and cannot be considered marginal due to its location near to wave natural excitation frequency in the deployment area. For ballast load case at 2 m/s towing speed, the heave peak is increased 5% respect to mooring case. At pitch peaks responses, all tested cases were lower than moored case but the peak values were decreased until lower point and return increases slightly again. More test cases are recommended to investigate this behavior in further study. Moreover, further numerical investigation on the fluid dynamic mechanisms related to the present study is needed.

Based on responses results and wave spectrum analysis, the maximum wind speed for towing operation is 11 m/s in order to avoid the wave excitation forces in this area. Towing with forward speed of 4 m/s at ballast load case not recommended as the pitch responses exceed the 5-degree pitch criteria. The results show that towing in light-ship load condition is more economical since the towing force is less than half of the ballast towing force with less motion responses.

Acknowledgements

This study was performed with support by the research project NO. 30707 (Mobile Reverse Osmosis Floating Desalination Platform Powered by Hybrid Renewable Energy), funded by the British Council and Science and Technological Development Fund (STDF). The authors acknowledge the University of Strathclyde's Department of Naval Architecture, Ocean and Marine Engineering and Desert Research Centre for the technical expertise and support provided during the period of research. The authors would also like to acknowledge the Kelvin Hydrodynamic Laboratory technician team including Steven Black, Grant Dunning, Bill Wright, Rebecca McEwan for their technical support through the model construction and experimental setup.

References

1- Tarek Abdel-Latif, Salwa T. Ramadan and Abeer M. Galal. Egyptian coastal regions development through economic diversity for its coastal cities. Housing and Building National Research Centre, 2012, Vol. 8, pp 252-262.

2- Egypt's Voluntary National Review 2018. Ministry of Planning, Monitoring and Administrative Reform, Cairo, Egypt.

3-Chouski, B. AquaTDPB3DP plants and systems: floating modular dismountable desalination equipment. Desalination Journal, Vol 153, 2002, pp 349-354

4-Chouski, B. AquaTDP/S3DP plants and systems. Floating ship-borne modular dismountable seawater desalination plant. Desalination, Vol. 165, 2004, pp 369-375.

5-Fadel, M., Wangnick, K., and Wada, N., Floating Desalination Plants an Engineering, Operating and Economic Appraisal. Desalination Journal Vol 45, 1983, pp 49-63.3- Offshore

Wind Technical Potential in the Arab Republic of Egypt. The World Bank, Washington DC 20433, March 2020.

6- Nadia Ashra and Islam Amin. Hybrid Floating Power Station driven by Renewable Energy for Saudi Arabia Coastal Areas. International conference on Electrical, Communication and Computer Engineering, ICECCE 2020, 12-13 June, 2020. (ISBN: 978-1-7281-7115-9).

7- Offshore Wind Technical Potential in the Arab Republic of Egypt. The World Bank, Washington DC 20433, March 2020.

8- Juan Amate, Gustavo D Sánchez and Gonzalo González. Development of a Semi-submersible Barge for the installation of a TLP floating substructure. TLPWIND® case study. Journal of Physics: Conference Series 749, 2016, 012016.

9- Amin, I., Ali, M., Bayoumi, S., Oterkus, S., Shawky, H. and Oterkus, E. Conceptual Design and Numerical Analysis of a Novel Floating Desalination Plant Powered by Marine Renewable Energy for Egypt. Journal of marine science and engineering, Vol. 8, 2020, pp 95. (doi:10.3390/jmse8020095).

10- Amin, I., Dai, S., Oterkus, S., Day, D. and Oterkus, E. Experimental investigation on the motion response of a novel floating desalination plant for Egypt. Ocean Engineering, Volume 210, 15 August 2020, 107535.

11- Amin, I., Ali, M., Bayoumi, S., Balah, A., Oterkus, S., Shawky, H. and Oterkus, E. Numerical Hydrodynamics-Based Design of an Offshore Platform to Support a Desalination Plant and a Wind Turbine in Egypt. Ocean Engineering, 2021, 108598.

12- Islam Amin, Saishuai Dai, Sandy Day, Mohamed E.A. Ali, Ahmed Balah, Hosam Shawky, Selda Oterkus and Erkan Oterkus. Experimental study on the motion response of an integrated floating desalination plant and offshore wind turbine on a non-ship platform. International Conference on Ships and Offshore Structures, ICSOS 2020, 1 – 3 September 2020, Glasgow, UK.

14- Kenneth Eik, Aleksey Marchenko. Model tests of iceberg towing. Cold Regions Science and Technology, Vol. 61, 2010, pp 13–28.

14- T. Nasar, S.A. Sannasiraj and V. Sundar. Motion responses of barge carrying liquid tank. Ocean Engineering, Vol. 37, 2010, pp 935–946.

15- Puyang Zhang, Yanqing Han, Hongyan Ding, Siyu Zhang. Field experiments on wet tows of an integrated transportation and installation vessel with two bucket foundations for offshore wind turbines. Ocean Engineering, Vol. 108, 2015, pp 769-777.

16- Puyang Zhang, Yanjian Peng, Hongyan Ding, Ruiqi Hu, Jianchao Shi. Numerical analysis of offshore integrated meteorological mast for wind farms during wet towing transportation. Ocean Engineering, Vol 188, 2019, 106271.

17- Puyang Zhang, Disheng Liang, Hongyan Ding, Conghuan Le and Xing Zhao. Floating State of a One-Step Integrated Transportation Vessel with Two Composite Bucket Foundations and

Offshore Wind Turbines. Journal of Marine Science and Engineering, 2019, Vol 7, pp 263. (doi:10.3390/jmse7080263)

18- M.N. Azzeri, O.E. Hanis, F.A. Adnan, M. Adi, P.A. Wilson, M.Z.Md.Zain. Drag Analysis Using Experiment and Numerical Study on the Design of Three Rudder Shaped Like (RSL) Bodies in Columns for Low Drag USV.

19- Design of Floating Wind Turbine Structures, DVN-GL rule, DNV-OS-J103, JUNE 2013.

20-Abdel-Raheem, S., Aal, E., Abdel-Shafy, A. and Abdel-Seed, F., Nonlinear Analysis of Offshore Structures under Wave Loadings. 15th World Conference on Earthquake Engineering 2012 (15WCEE), 24-28 September 2012, Lisbon, Portugal.

21- Technical Standards Committee Guidelines for Marine Transportations. DNVGL-ST-N001. Noble Denton Group Limited, 2015.

22- Lars Bergdahl. Wave-Induced Loads and Ship Motions. Department of Civil and Environmental Engineering, Division of Water Environment Technology, Chalmers University of Technology, Report No. 2009: 1, ISSN 1652-9162, 2009.

23- Transport and installation of wind power plants. DNV GL-ST-0054, June, 2017.