Experimental Comparison of Dynamic Responses of a Tension Moored Floating Wind Turbine Platform with and without Spring Dampers

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Abstract. The offshore wind industry is rapidly maturing and is now expanding to more extreme environments in deeper water and farther from shore. To date fixed foundation types (i.e. monopoles, jackets) have been primarily used but become uneconomical in water depths greater than 50m. Floating foundations have more complex dynamics but at the moment no design has reached commercialization, although a number of devices are being tested at prototype stage. The development of concepts is carried out through physical model testing of scaled devices such that to better understand the dynamics of the system and validate numerical models. This paper investigates the testing of a scale model of a tension moored wind turbine at two different scales and in the presence and absence of a spring damper controlling its dynamic response. The models were tested under combined wave and wind thrust loading conditions. The analysis compares the motions of the platform at different scales and structural conditions through RAO, testing a mooring spring damper for load reductions.

1. Introduction

The first offshore wind farm was commissioned in 1991 and since then the total European offshore installed capacity has risen to greater than 7.3GW [1]. Offshore wind offers a number of advantages over onshore wind, including, higher wind speeds, larger turbines possible, no site access restrictions, larger sites available, reduced turbulence and lower wind shear [2]. As shallow water, nearshore sites are depleted or countries with no shallow continental shelf seek to develop offshore wind, the industry must look to deeper water sites. In water depths greater than 60m floating platforms begin to become economical [3]. In Ireland there is the potential for 25-27GW of offshore floating wind [4]. Tension moored platforms are one floater type generating a great deal of interest. The platform is restrained due to excess buoyancy providing tension in the mooring lines. Part of the development process for such type platforms involves scaled model tests in wave basins. Testing of small scale devices typically 25-100th scale is carried out in an ocean wave basin. This testing is vital to understand the interactions between hydrodynamic and aerodynamic loading. Varied structural settings can be recreated relating to both the operational and survivability conditions. In this paper, a novel floating platform is tested in a deep-water wave basin where adjustments are made to the mooring stiffness in order to reduce peak mooring loads.

2. Scaled Tests

Model testing of tension leg platforms (TLPs) have been carried out at scales of 1:100 [5] and 1:50 [6, 7]. These tests involve Froude scaling of both the hydrodynamics of the floater and aerodynamics of the wind turbine. These tests produce Response Amplitude Operators (RAOs) which help benchmark the performances and often act as a guiding factor for more detailed modelling or testing at a larger scale or for an actual deployment in offshore conditions.

There are four main methods for modelling wind turbine loading on a floating platform; **1) Mechanical Pulley System:** Constant horizontal load applied through a mass hanging via a pulley from the nacelle [8]. **2) Ducted Fan:** A ducted fan with high revs/min that is attached to the top of the tower. A constant or variable wind thrust can me modelled, and with the inclusion of a feed-back loop, which includes the motions of the platform, the relative (between incoming wind and platform motion) wind thrust can be applied [9]. **3) Applied Wind on Disk:** Wind is generated using an array of fans and applied to a thin disk. A drag coefficient of 1.2 is used to model the thrust force [10]. **4) Applied Wind on Model Turbine:** Wind is generated using an array of fans, and applied to a model turbine. As Froude scaling and Reynolds scaling (required for wind blade lift modelling) are not compatible (either thrust force of aerodynamic damping being incorrect) turbine blade geometry must be modified to include longer chord lengths in order to correctly model all effects [11]. Advantages of this method over the previously mentioned include correct modelling of aerodynamic torque and the gyroscopic effect of the rotor [12]. The gyroscopic effect can be compensated for in the first three modelling methods by attaching a motor and simple mass rotor that turns at the correct revolutions per minute.

3. Monitoring

As offshore wind turbines move to more severe environments the need to monitor loadings and platform performance become more important. Environmental observations required include metoocean data such as wind and wave climate. Platform and turbine conditional monitoring includes Platform motions in degrees of freedom, mooring loads, turbine and blade parameters such as pitch and yaw. These parameters are relevant to the testing of platforms at model scale and in the case of this study it is the motions and mooring loads that are most relevant.

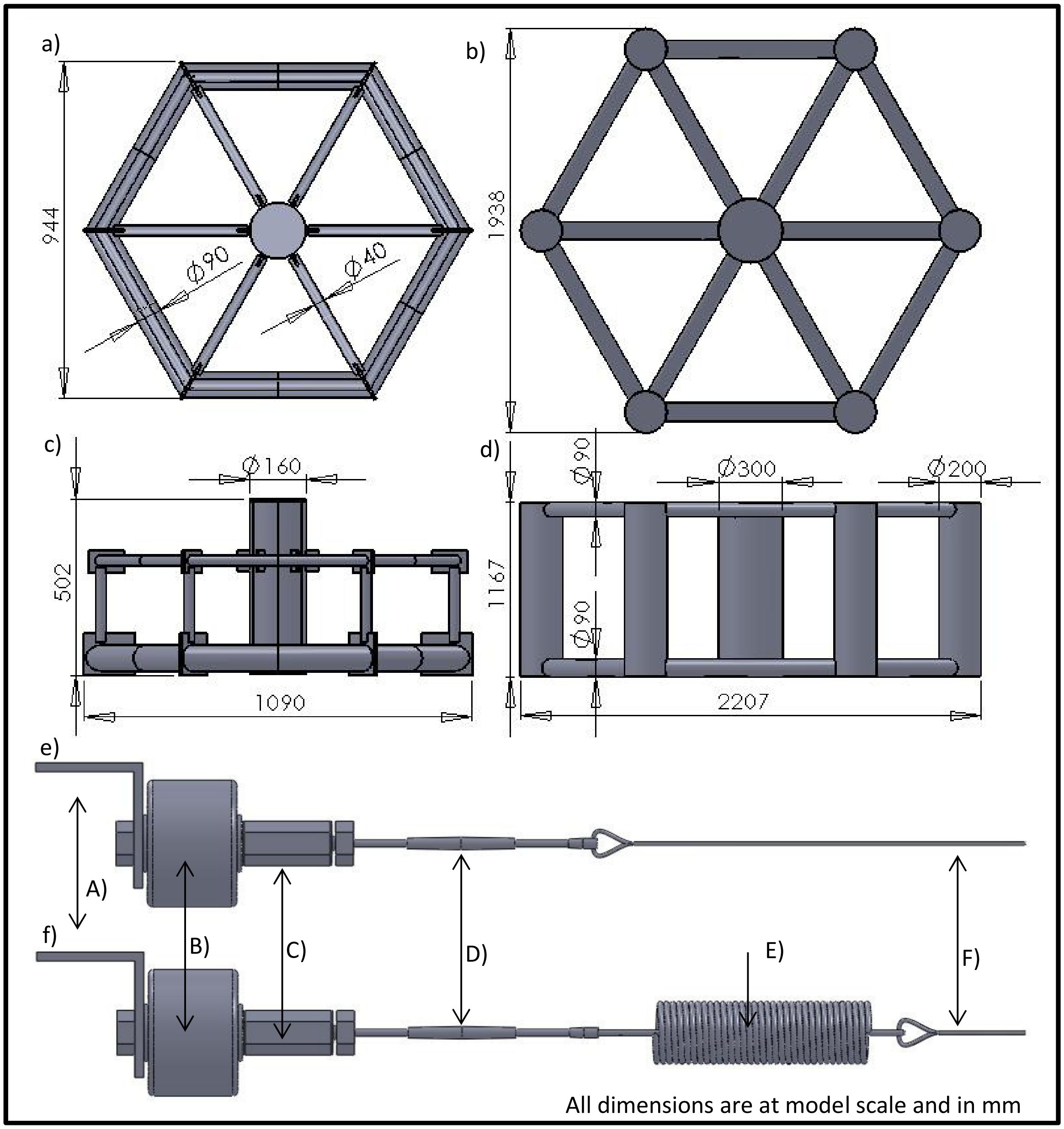

Fig 1.a) Platform 1 Plan λ =50. b) Platform 2 Plan λ = 30 c) Platform 1 Elevation λ =50. d) Platform 2 Elevation λ = 30. e) Mooring Configuration without Spring Damper. f) Mooring Configuration with Spring Damper. A) Fixing Bracket, B) Load Cell, C) Extension Nut, D) Tie Rod, E) Damper Spring, F) Mooring Line.

4. Experimental Setup

Testing was undertaken on two TLPs of similar design at different scales. Both floating platform has the characteristics of a semi-submersible but are moored with vertically tensioned lines and support NREL's 5MW reference turbine [13]. The first platform has a scale of 1:50 (figure 1a& c) and is described in detail in [14]**.** The second TLP tested (figure 1b& d) is a truss-type structure with a floating hexagonal platform which in the model tests was connected by six mooring tethers to a rigid base located at a depth of 5m (basin depth was 10m). The model was scaled according to Froudian scaling laws and has scale of 1:30 and the floating hexagonal platform consists of six outer and one central buoyancy column(s). The outer buoyancy columns consists of six 0.2m diameter polyvinyl chloride (PVC) pipes, joined to the central column by twelve (six top and six bottom) 0.09m diameter PVC pipes. The outer buoyancy columns are also connected to each other by twelve (six top six bottom 0.09m diameter PVC pipes. The central column was fabricated from 0.3m diameter PVC pipe and provides sufficient buoyancy to counteract the weight of the tower and nacelle. The excess buoyancy force was passed to the six mooring lines made of 3mm diameter stainless steel wire to ensure that they remain in tension at all times. The weight of the TLP was 121.1kg. The wind turbine tower was 2.58m high and was fabricated with a 0.07m diameter stainless steel pipe (7.4 kg) with the thrust load applied using a high revolutions per minute ducted fan (0.75kg), according to the wind speed thrust load curve given in [13]. As the thruster was not heavy enough to model the turbine, additional lead weights are also placed at the top of the tower (8.5 kg). Each wind load case involved a constant wind speed which was verified by a bending load cell connecting the fan to the tower, as can be seen in fig 2.c.

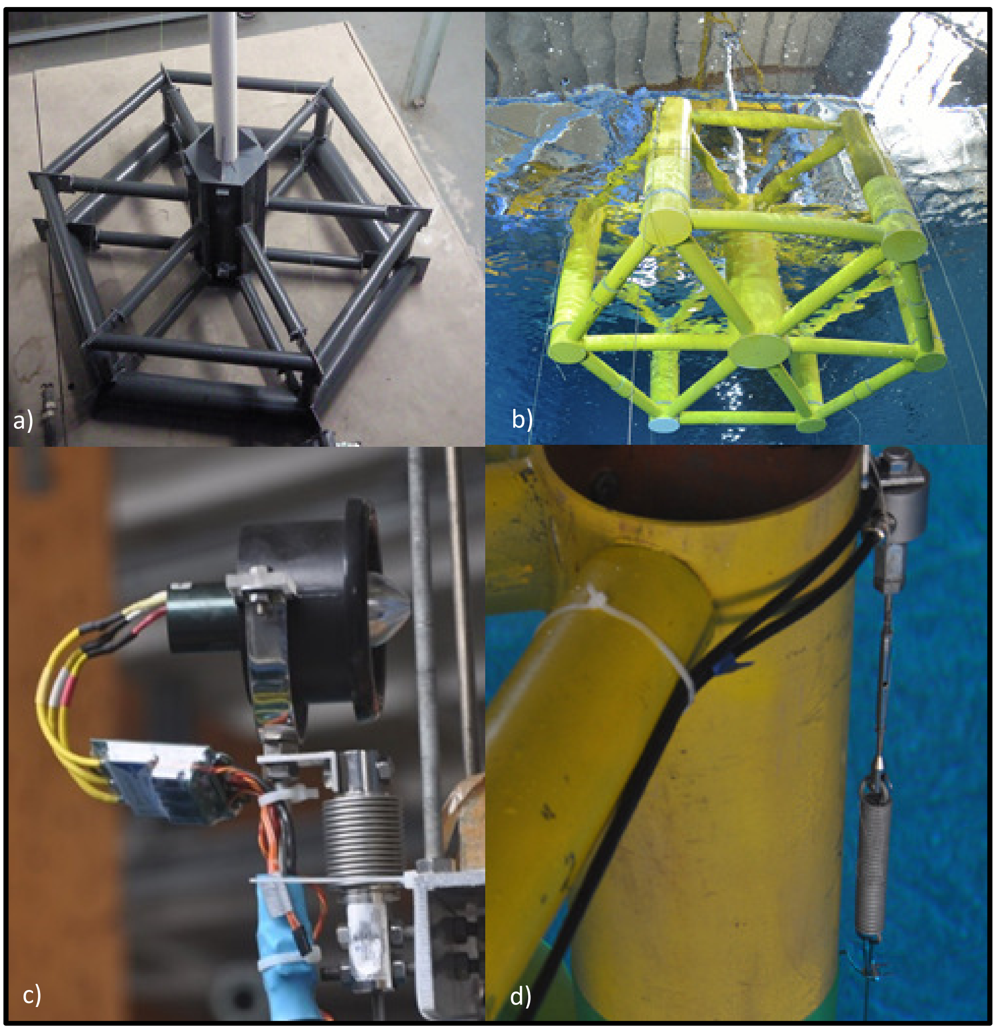

Fig 2.a) Platform 1 λ =50. b) Platform 2λ = 30 *Photo Credit IFREMER*. c) Thrust Generation. d) Mooring Spring Damper

A second mooring case was modelled, where a high stiffness extension spring (6N/mm) was added to each of the 6 mooring lines (fig 1.f). The spring has a pre-tension of 130N meaning the change in stiffness will only be noticed in extreme wave conditions. It was designed such that the motion of wind turbine will be constrained during operational wave conditions and that during extreme wave conditions this constraint will be relaxed allowing the platform to move and thus reducing the peak mooring loads. The TLP was tested in the deep water basin, in IFREMER, Brest, France. The tank is 50m long, 12.5m wide and 10m deep. Panchromatic waves of a Bretschneider (BS) spectrum were generated using a single hydraulic v-shaped wave plunger, and reflections absorbed at the opposite end by a porous parabolic beach. Waves were measured using two servo-controlled wave gauges, motions were captured using three Qualisys motion tracking captures picking up four UV markers, mooring loads were measured with six 500N load cell.

5. Results

All results are shown and compared at prototype scale for standardisation purposes. Figure 3 shows the comparison between surge RAO's for wave loading only for the two different scaled floaters (λ =30 and λ =50) It must be noted that a number of differences exist between the models. This can be attributed to the change in shape of floater, main buoyancy has moved from horizontal ring in λ =50, to vertical ring in λ =30, which greatly increases the water plane area. Also there is a change in initial tension between platforms, 1.55 MN (λ =50), and 2.44 MN (λ =30), a change in floater diameter, 47.2m (λ =50), and 58 m (λ =30), and also a change in water depth, 50m (λ =50), and 150 m (λ =30). 150m being the design water depth and 50m from shallow tank constraints. These changes explains the difference in peak surge frequency from 0.035 Hz (λ =50) to 0.021 Hz (λ =30). As the scale increases it can be seen that the consistency of the results improve.

Figure 4 compares the second mooring case, including the high stiffness extension spring to each mooring line. It shows how the addition of the spring dampers to the mooring lines affects the surge RAO and mooring tension RAO for three wind cases (Constant wind speeds of $0ms^{-1}$ (No thrust), $25ms^{-1}$ (Medium thrust), and $11.5ms^{-1}$ (Max thrust). It can be seen that the springs had the intended effect of reducing the surge stiffness, thus increasing the surge displacement, and decreasing the mooring tension RAO. As surge and pitch are coupled in TLPs a large increase in the pitch RAO was also noted as expected.

Figure 5 shows the surge set-back time series and surge energy of the platform under wind loading of $25ms^{-1}$ and $11.5ms^{-1}$. The natural surge frequency of the platform is seen to increase as wind thrust loading increases as follows: 0.0195 Hz in no wind, 0.0197 Hz in $25ms^{-1}$ and 0.0209Hz in $11.5ms^{-1}$. Differences in the time-series and spectral energy for the same wind thrust loading were deemed to come from transverse waves which had not completely dissipated before testing had begun.

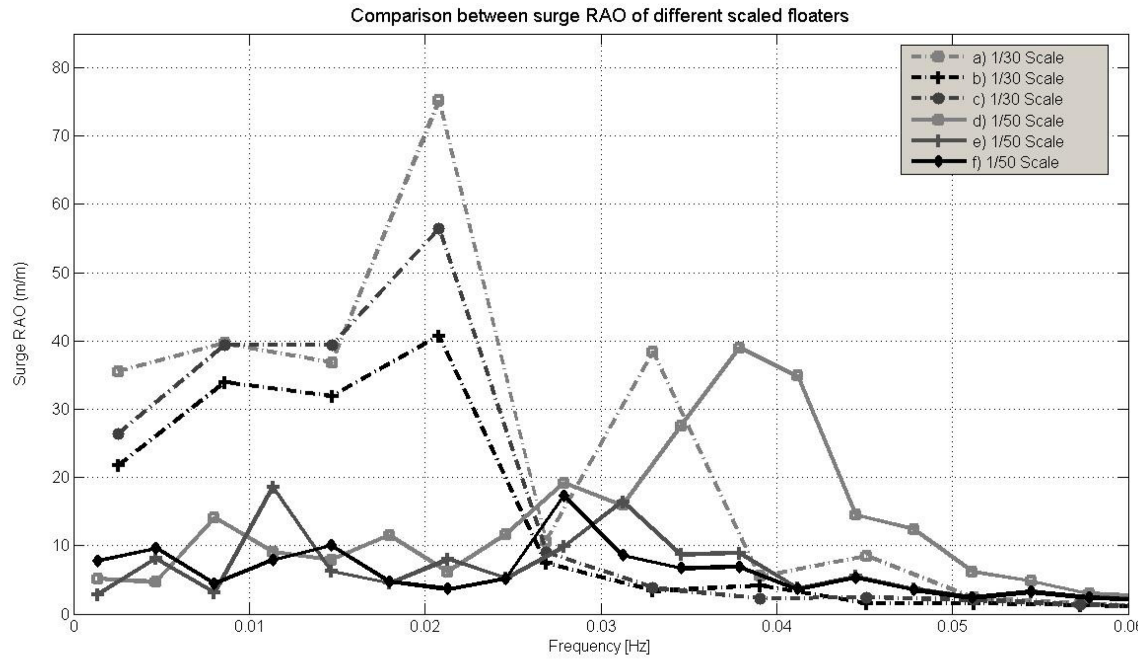

Fig 3. Comparison Between Model Scale λ =30 and λ =50. a) BS Hs 6.6m Tp 11.5 b) BS Hs 8.7m Tp 13s c) BS Hs 6m Tp 12s d) BS Hs 3m Tp 7.6s, e) BS Hs 3m Tp 17.7s, f) BS Hs 3m Tp 19.2s

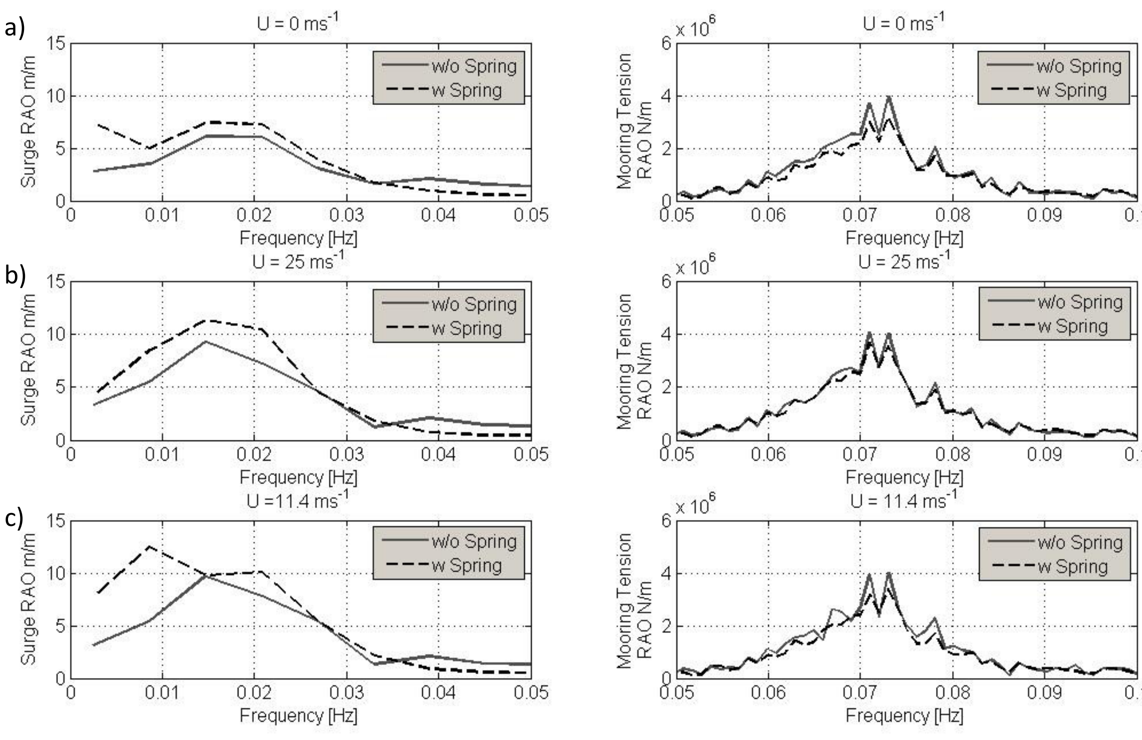

Fig 4. Comparison of Surge RAO and Mooring Tension RAO without Spring and with Spring Damper, for Wind Speeds of 0 (a), 25 (b), 11.4 (c) ms^{-1}. Hs = 9m, Tp = 18s, Model Scale λ =30

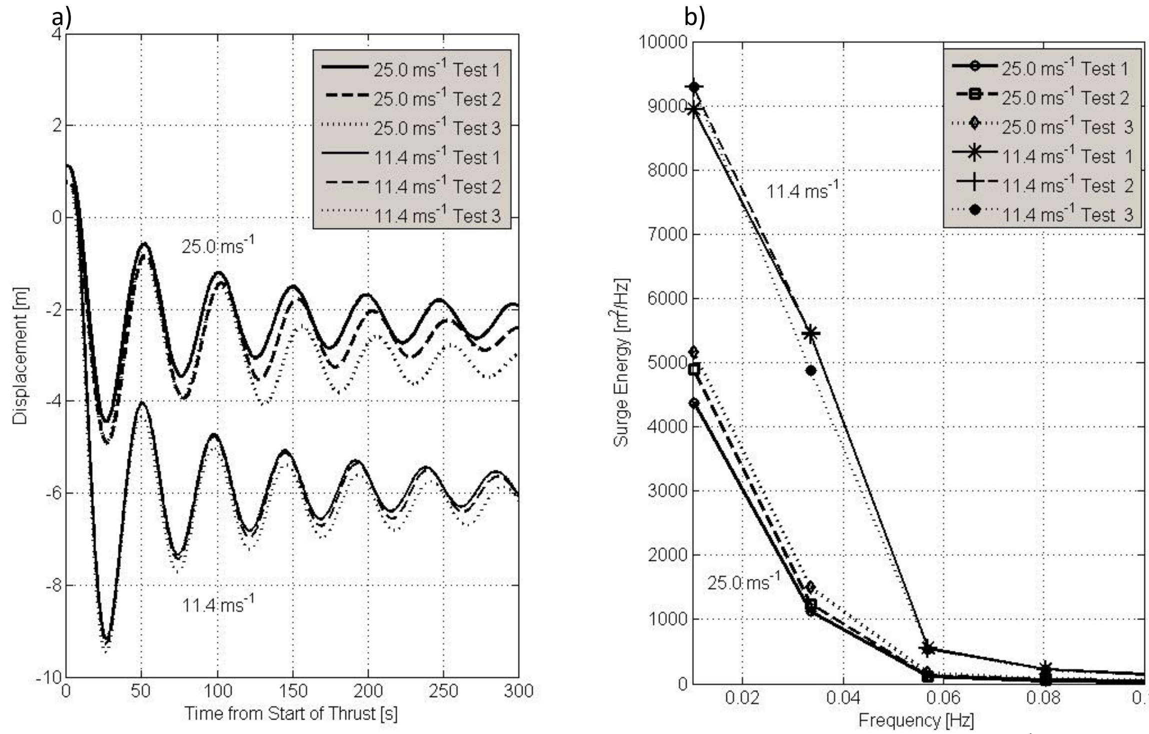

Fig 5. Still Water Surge Displacement (a) and Surge Energy (b) from a Wind Loading of 25 ms^{-1} and 11.4 ms^{-1}, Model Scale λ =30

6. Conclusion

This paper compared the RAO's of two floating platforms as the design evolves through the development proves. It shows the importance in terms of reliability in testing at larger scales. This testing successfully showed and benchmarked the capabilities of the platform in operational and survivability states. There was a large increase in the maximum dynamic response of the system when the spring damper was implemented (25-33%), this had the intended effect of reducing the maximum mooring load (11-25%). A slight increase in higher frequency surge motion of the platform was detected and was deemed to be an effect of the increased pitch motion. The spring damper was demonstrated at a proof of concept level for reducing mooring line tension through softening the restoring stiffness. More testing of this is envisaged in the future. The maximum mooring line force holds a great deal of importance in determining the capital cost of the floater, mooring line and mooring foundation (piles or gravity base) and thus any reduction would be extremely important to the future of deploying wind turbines on these kinds of platforms. Determining natural frequencies and there variance due to wind loading are vital for validating numerical models, and has been demonstrated here.

7. Acknowledgements

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