Design and analysis of a semi-submersible floater supporting two 5MW wind turbines

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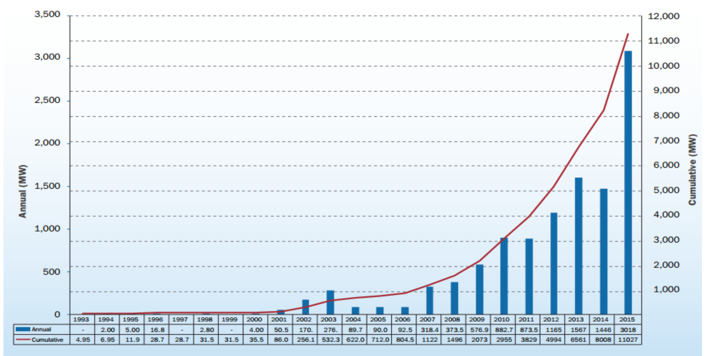
Introduction

As one of the few commercialized clean energy technologies, offshore wind industry is experiencing a rapid growth due to the urgency of global environmental issue and international agreement on the clean energy revolution.


(a) Installation

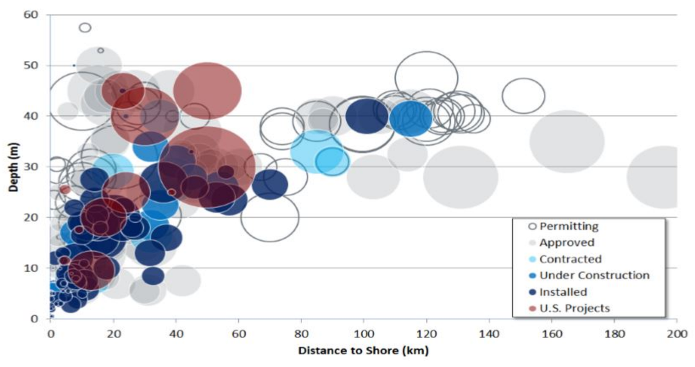

(b) Project depth and distance

Figure: Offshore wind trends

Fig 1b shows a deep water trend among the industry during engineering practices. New offshore wind turbine structure concepts ought to be developed after a water depth of 50m, where current commercial substructures of offshore wind turbines, such as gravity, jacket and monopile, become economically limited.
It is widely accepted that the cost increase of offshore wind turbines is not very sensitive to the increase of floater size. Therefore using multiple wind turbines on a single floater could be a good way to reduce cost.
The goal of this master thesis is to study the responses of the structure when two turbines are present and develop fundamental understanding of the motion responses from a combination of wave forces and two turbine aerodynamic forces.

Objectives

To understand the responses of a semi-submersible floater with double turbines, the goal is broken down into five major steps.

- Design of the offshore wind turbines and spread sheet hydrostatic calculation
- Finite Element Modelling and hydrostatic calculation
- First order frequency domain hydrodynamic calculation & analysis
- Second order frequency domain hydrodynamic calculation & analysis
- Time domain response calculation & analysis taking into account wind loads, wave loads and mooring system stiffness.

Theory

The motion equations are established based on potential theory, where the problem is divided into diffraction problem and radiation problem. To examine the first order frequency domain hydrodynamics, the governing equation for this specific structure can be written as,

$$(M + A(\omega))\ddot{\eta}_{WF} + (B(\omega) + D_1)\dot{\eta}_{WF} + C\eta_{WF} = F^{(1)}_{wave} \quad (1)$$

where M is the mass, $A(\omega)$ added mass, $B(\omega)$ potential damping, D_1 the linearized viscous damping coefficient from Morison equation, C the hydrostatic restoring coefficient.
For this semi-submersible floater, the concerns on second order frequency domain lie in the difference-frequency terms because the natural frequencies are low at all DOFs and difference-frequencies second order forces might excite resonances. For second order frequency analysis, governing equations follows,

$$(M + A(\omega = 0))\ddot{\eta}_{LF} + D_1\dot{\eta}_{LF} + D_2 f(\dot{\eta}_{LF}) + K\eta_{LF} = F^{(2)}_{wave} \quad (2)$$

where, $B(\omega = 0) = 0$, the potential damping is therefore excluded from the equation. D_2 are the second order viscous coefficient.
The time domain governing equations, as the instantaneous and most sophisticated description of the problem, take into account first order wave force, second order wave loads, wind loads from both turbines and mooring effects. Mathematically, the governing equation can be expressed as,

$$(M + A_\infty)\ddot{\eta}(t) + \int_0^t K(t-\tau)\dot{\eta}(\tau)d\tau + C\eta(t) = F^{(1)}_{wave} + F^{(2)}_{wave} + F^{(1)}_{turbine} + F^{(2)}_{turbine} + F_{mooring} \quad (3)$$

where K is the retardation function, which can be found by frequency-dependent added mass.
It should also be noted that due to the presence of mooring system, M, A and C are also altered to include the mooring lines.

Good to know

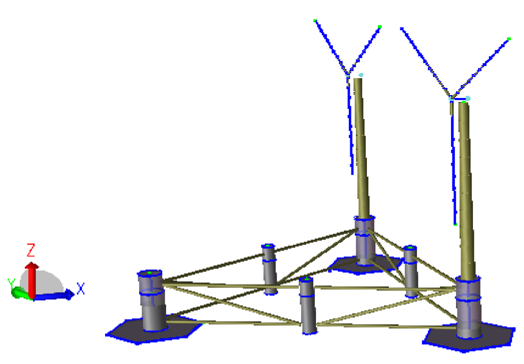
The first order wave forces are a function of structure geometry and wave spectrum. In the study, JONSWAP wave spectrum is used for wave loads and Kaimal spectrum is used for wind loads.
Eq (1) shows that the responses of the of structure should follow the wave forces, with a phase shift.
Eq (2) indicates that second order responses will be more significant when wave frequencies are high. Theoretically, second order forces dominate when $\omega \to \infty$
Eq (3) basically considers the major external forces the structure is exposed to. Therefore the responses are more close to reality. Behavior of the double turbine motions will be discussed based on the time domain results. Mooring lines are added in DNV software SIMA and aerodynamic forces from two turbine are simplified as external force using TDHMILL.

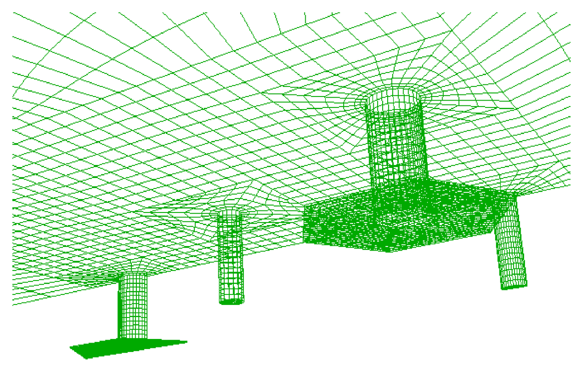
Modelling

After a simple spreadsheet calculation, the turbine model is initiated with reference to the concept WindFloat, Wind2Power and Hexicon. FEM model is built in DNV software GeniE. The GeniE model is double checked by comparing with matlab estimation, as shown in Tab 1. The NREL land-based 5MW wind turbines are used for the study. A weathervane mooring system is designed such that the ends of mooring lines are attached to the front column.

Table: Mass of the structure without ballast

	Component	Matlab $[t]$	GeniE$[t]$	Error $[\%]$
	Hub	56.78	56.78	0
	Nacelle	240.00	240.00	0
	3 Blades	53.22	53.11	0.206
	Tower	347.46	347.46	0
2 Turbines	Overall	1394.92	1394.71	0.015
	Side Columns	320.60	319.55	0.327
	Middle Columns	183.48	181.29	1.194
	Braces	90.36	90.40	0.044
	Heaveplates	799.00	798.90	0.013
Floater	Overall	5587.88	5556.19	0.567
Total		6982.80	6950.90	0.457


(a) Turbine CAD Model


(b) Bottom View of FE Model

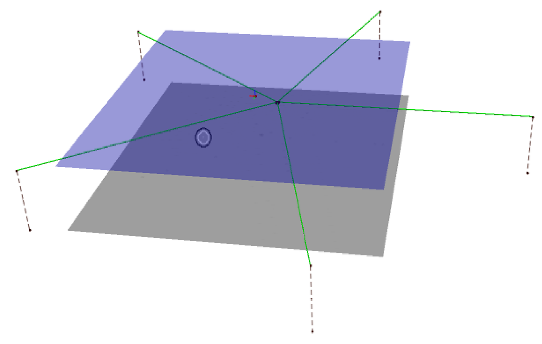

(c) Mooring System

Figure: Structure Modelling

Results & Discussion

Hydrostatic result is shown in the figure below. The dashed line is the estimated wind heeling moment,

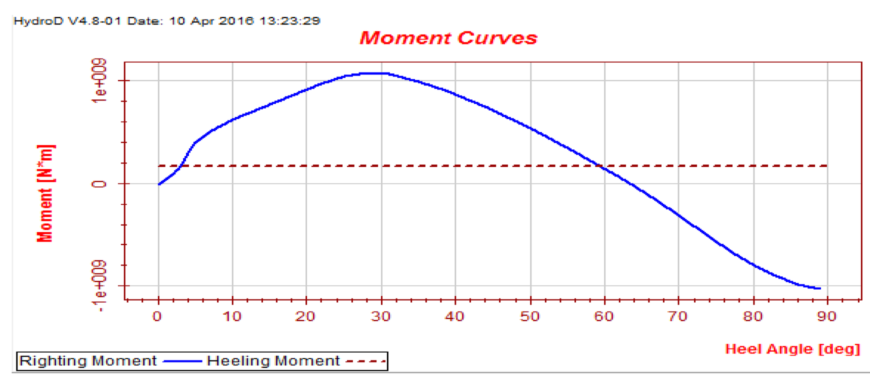
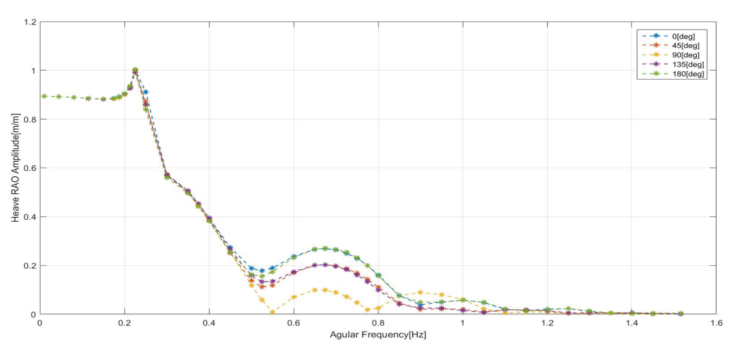


Figure: restoring moment as a function of heeling angle

In the linear hydrodynamic results, peaks of motions correspond well with the peaks of force amplitude RAO, as demonstrated in Figure 4. A clear causal relationship is confirmed between the external forces and responses. The only exception is at $\omega \approx 0.25rad/s$, the heave eigenfrequency, where the resonance is excited and large responses are expected.


(a) Motion

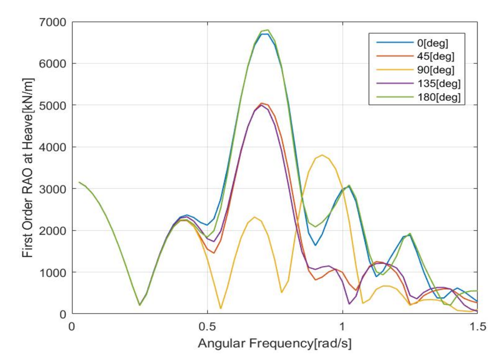
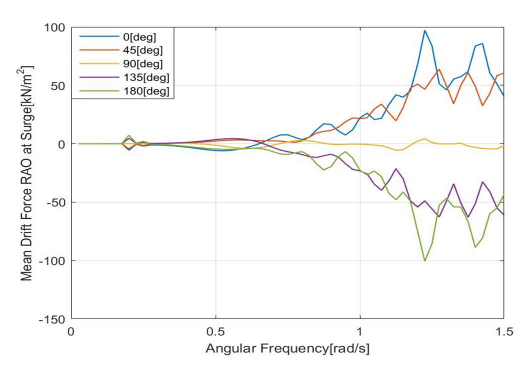
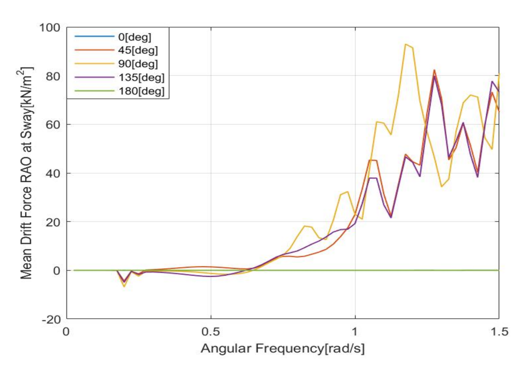

(b) Force

Figure: Heave Linear RAO

Specific attention is paid to surge sway and yaw while examining the second order forces because eigenfrequencies are 0 at these DOFs if the mooring system is not added. Generally, it can be observed that mean drift forces become more significant for higher wave frequencies, as expected.
It is seen that the maximum linear wave excitation forces to be about $10^3\xi_a(kN) - 10^4\xi_a(kN)$ while the horizontal mean drift force is about $10^2\xi_a^2(kN)$.


(a) Surge


(b) Sway

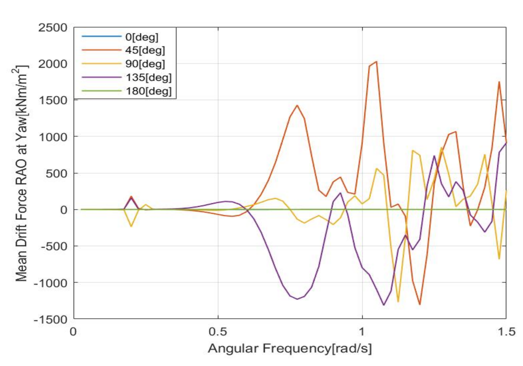

(c) Yaw

Figure: mean drift force as a function of wave frequency

TO BE CONTINUED...

So far, the behavior of the semi-submersible hydrodynamics is just as expected. More interesting behavior might be observed accounting the wave, wind and mooring loads together. Currently, the time domain simulation tool SIMO-RIFLEX-TDHMILL is being debugged.