École Centrale de Nantes

Marine Technology - Hydrodynamics for Ocean Engineering
European Masters Course in Integrated Advanced Ship Design

Design and Feasibility Study of an Anti-Roll Tank for Floating Offshore Wind Turbine Foundation

Master Thesis

Submitted by:	Marea Anna FRAZEL (180656K)
Academic year	2018-2019
Date of submission:	September 10, 2019

Acknowledgements

I would like to thank my parents, Denis and Rowena Frazel, for endowing me with the love of learning and a fascination with the ocean, as well as acknowledge their relentless support of all my pursuits. To Riccardo Mariani and Thomas Choisnet, I would like to express my very great appreciation for your guidance, questions, and encouragement throughout this master's thesis. I am very grateful for your decision to invite me to Ideol, and for everything I've learned in the past 6 months. Thank you as well to the Ideol team-especially Stéphane Toumit, Adrien Courbois, and Jean-Noël Dory for your valuable input.

Thank you to the professors at École Centrale de Nantes, in particular Guillaume Ducrozet, Lionel Gentaz, and Jean-Christophe Guilloteaux for their excellent formation and endowing interest in hydrodynamics and marine renewable energy. Thank you to the EMship team, especially Philippe Rigo, for a great education in naval architecture and invaluable career support. Thank you to my dear friend Anja Schnepf, for two years made less difficult and a fair bit more fun with you by my side. Finally I would like to thank my incredibly supportive partner, Tim Müller-Wolf, for his kind understanding with my frustrations, joyful celebration with my successes, and ceaseless love.

0 Executive Summary

Introduction The goal of this master's thesis is to investigate the feasibility of an anti-roll/pitch tank for Ideol's floating offshore wind turbine foundation, the 1X MW SQUATINA project, and Ideol's offshore substation, the Optifloat project. The roll and pitch responses of a FOWT foundation are important to consider and mitigate, as they impact the loads in the wind turbine components, transition piece, hull and mooring system components. An anti-roll/pitch tank would conceptually reduce the dynamic response of the foundation to the waves. The desired effect would be replacing the damping plates, which have detrimental effects on drift loads and structure design. Limiting the floater's motion might also improve production performance, or influence the sizing of the mooring system.

0.1 Ideol

Ideol is an engineering firm founded in 2010 concentrating on floating foundations for offshore wind. The firm accompanies offshore wind projects from conception to installation. The team's acclaimed innovation, the Damping Pool®is featured in the floater models for both the SQUATINA project and the Optifloat. Ideol has two demonstrators in France and Japan- the 2MW Floatgen (with a concrete hull) off the coast of Saint Nazaire, and the 3MW Hibiki (with a steel hull) in Japan.[21]

0.1.1 SQUATINA 1X MW Floating OffShore Wind Turbine

The SQUATINA project is Ideol's upscaling, optimization, industrialization and cost reduction of their hull to suit a 12 MW wind turbine. [23] Their first demonstrator, the 2MW Floatgen equipped with the Ideol floating foundation, has been fully validated and is ready for commercial-scale deployments. This project has ensured the functionality of Ideol's floater design, as well as provided important lessons. In preparing for the future sizing of wind turbines (only this past year have the first 10MW turbines from Vestas and Siemens Gamesa been launched), Ideol has prepared a design for the future commercialization of floating offshore wind farms for these double-digit wind turbines.[15] [9]

0.1.2 Optifloat Floating Substation

An electrical floating substation is a structure that provides the scaffolding for the systems to collect and export the power collected by the wind turbines. In addition to transmitting the electricity to shore, they also stabilize the power voltage from the various units and reduce electrical losses. The electricity is then fed to the transmission grid via submarine cables.[14]

Ideol coupled with Atlantique Offshore Energy to design the world's first floating electrical offshore substation, dubbed Optifloat. It combines Ideol's patented and shallow-draft Damping Pool®concept with AOE's certified electrical offshore substation concept SeeOs. This is a universal and modular structure and is thus suitable for both bottom-fixed and floating offshore wind farms starting at depths of 40 metres.[4]

Anti-Roll Device Decision and Justification The following was taken into account in order to arrive at the decision to pursue the development of a U-tube anti-roll tank. For the free surface tank, the issue with sloshing decreases the efficacy of the theoretical yield. For external tanks, there is the disadvantage of hull corrosion due to seawater in the cut-out reservoirs. Additionally, it was undesirable to remove sections of the Ideol hull. A moving weight has multiple, heavy parts and thus would complicate the installation (whereas a tank would simply have to be filled with water). A controlled-passive or an active system would include a valve system and a require control feedback system, or a pump controlled system. While this is certainly possible, this would additionally complicate the design- for a 20 year installation, it would be difficult to ensure that the valves, motors and pumps would suffice, and it is possible that there is already a significant decrease in the roll amplitude using a passive U-tank. Another active system, fin stabilizers would be insufficient because there is no forward speed. Finally, gyro stabilizers cause highly concentrated loads and are rather costly, which is undesirable.

There has been many proven installations demonstrating the efficacy of U-tanks. Given such, there is a broad availability of research for modelling and design of the system. Thus, the passive U- tank was chosen as the appropriate system to investigate.

Description of U-Tank Function Herr Frahm applies the laws of resonance to "utilise a secondary and artificial resonance in order to annihilate the influence of the primary resonance between waves and ship". The water column in the U-shaped tank oscillates with same resonant frequency as the ship. The efficacy of the system is described as follows. "According to the law of resonance, the phases of the impulse of waves and ship are deferred by 90 deg. The same law applies to the rolling of the ship, and the oscillating movements of the tank water produced by the former. Also, in this instance, the phases are deferred by 90, and the tank water will reach its highest or lowest level in the vertical parts a quarter of a period later than the greatest heeling of the ship to one side or the other." Thus, the moment created by the U-tank acts in the opposite direction to the impulse of the waves.

0.2 Methods

This project is divided into two models. The first is an analytical, linear model of the floater-tank system developed by the author, based on the 4DOF solution in Seakeeping: Ship Behaviour in Rough Weather [26], and implemented as a code in MATLAB, a numerical computing environment, and thenceforth denoted as the MATLAB model. The second is the 7DOF nonlinear model of the Ideol floater, provided by Ideol, and coupled with an external function that implements the influence of the tank on the floater as a force. In order to understand the models, the frame of reference and the equations of motion will be described for the solutions, as well as the calculation meothods for the Python external function.

0.2.1 MATLAB model

The analytical (linearized) model is simulated by MATLAB in the frequency and time domain. The anti-roll tank is (preliminarily) sized on the basis of these simulation through parametric studies. The model is based off the theory for U-tube passive tanks, developed by Stigter in 1966 [37] and modified by Lloyd in 1989 [26], which is to be presented below.

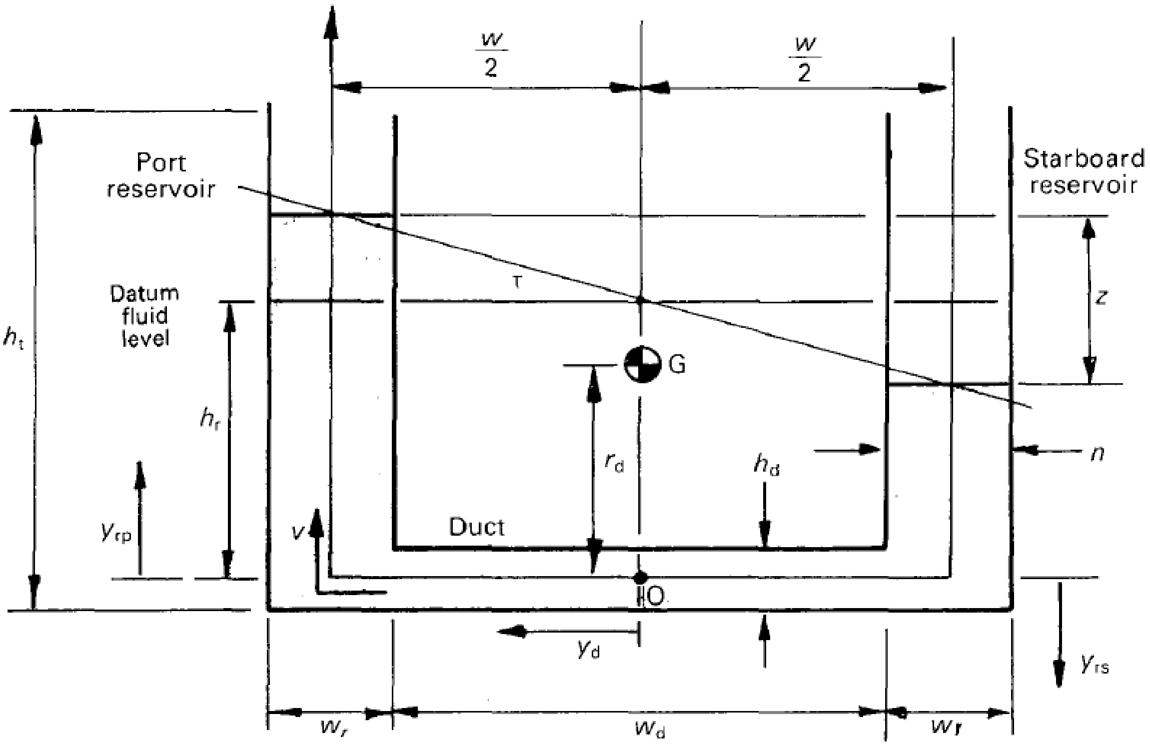

Figure 1: Axis system and tank dimensions [26]

The tank consists of two reservoirs with a connecting duct, all with constant rectangular cross-sections. The axis system and tank dimensions are defined in Figure 1. The origin O is at the midpoint of the central duct. The nomenclature is defined as follows.

7 Degree of Freedom Solution The complete equations of motion for a ship with an anti-roll tank in matrix form is thus:

$$[A][\ddot{X}] + [B][\dot{X}] + C[X] = [F] \tag{1}$$

Where

Table 1: Tank Nomenclature

Symbol	Definition	Unit
h_t	Tank column height	[m]
$h_r = h_t/2$	Fluid height	[m]
h_d	Duct height	[m]
w_r	Column width	[m]
w_d	Duct width	[m]
w=w_d+w_r	Column centerline width	[m]
r_d	Vertical distance to global COG (positive meaning below COG)	[m]
τ	Tank angle	[°]
x_t	Tank width in transverse direction	[m]
z	Difference in the height of the fluid level	[m]

$$\begin{bmatrix} Surge \\ Sway \\ Heave \\ Roll \\ Pitch \\ Yaw \\ Tau \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & I_{22}+a_{22} & 0 & a_{24} & 0 & a_{26} & a_{2\tau} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{42} & 0 & I_{44}+a_{44} & 0 & a_{46} & a_{4\tau} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{62} & 0 & a_{64} & 0 & I_{66}+a_{66} & a_{6\tau} \\ 0 & a_{\tau 2} & 0 & a_{\tau 4} & 0 & a_{\tau 6} & a_{\tau\tau} \end{bmatrix} \begin{bmatrix} \ddot{X}_1 \\ \ddot{X}_2 \\ \ddot{X}_3 \\ \ddot{X}_4 \\ \ddot{X}_5 \\ \ddot{X}_6 \\ \ddot{\tau} \end{bmatrix} +$$

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b_{22} & 0 & b_{24} & 0 & b_{26} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b_{42} & 0 & b_{44} & 0 & b_{46} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b_{62} & 0 & b_{64} & 0 & b_{66} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & b_{\tau\tau} \end{bmatrix} \begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \\ \dot{X}_5 \\ \dot{X}_6 \\ \dot{\tau} \end{bmatrix} + \tag{2}$$

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{26} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & c_{46} & c_{4\tau} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} & 0 \\ 0 & 0 & 0 & c_{\tau 4} & 0 & 0 & c_{\tau\tau} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ \tau \end{bmatrix} = \begin{bmatrix} 0 \\ F_{w2} \\ 0 \\ M_{w_4} \\ 0 \\ M_{w_6} \\ 0 \end{bmatrix}$$

0.2.2 Tank Natural Frequency, Dimensioning,and Internal Damping

Re-arranging the tank equation in the form of a linear damped spring-mass system:

$$a_{\tau\tau}\ddot{\tau} + b_{\tau\tau}\dot{\tau} + c_{\tau\tau}\tau = -(a_{\tau 4}\ddot{x_4} + c_{\tau 4}x_4 + a_{\tau 2}\ddot{x_2} + a_{\tau 6}\ddot{x_6}) \tag{3}$$

Then the natural frequency of the tank is

$$\omega_\tau = \sqrt{\frac{c_{\tau\tau}}{a_{\tau\tau}}} = \sqrt{\frac{2gh_d}{w_r w + 2h_r h_d}} \qquad \text{[radians/second]} \quad (4)$$

The goal is then to design the tank to match the natural frequency of the floater. The floater natural frequency is taken from the Orcaflex model. This was done by performing a decay test, with a starting rotation of 10 degrees. This was compared to the response amplitude calculations for the frequency domain for accuracy. The response amplitude calculations were performed by running a batch script and determining the floater response and RAO for the periods $T=$ 3:60 at a wave height of H=5 using an airy wave model. This is a more consistent method for determining the linear response at difference frequencies for the floater, than performing a test using an irregular wave train and determining the RAO with that floater response.

0.3 Python Coupling with Orcaflex

The MATLAB model provides the solution of the tank-floater system in the time domain and the frequency domain, as well as providing the frame for comparing the results to the floater (without tank) response generated by Orcaflex. The subsequent step is implementing the effect of the designed tank into the Orcaflex model.
The method used for the coupling into Orcaflex is a Finite Difference Discretization of the solution for the equation of motion of the 1DOF tank system. This method is presented in "Finite Difference Methods for Vibration Problems".[25]

0.4 Python Implementation

The important consideration in implementing this method in Python was defining the boundary conditions for the tank. The boundary condition is defined as the maximum angle that the tank can reach, τ_{max}, which is achieved when one reservoir is completely full and can be determined with:

$$\tau_{max} = arctan(\frac{h_t - h_d}{w}) \qquad (5)$$

The next step is determining the state of the floater and calculating what the response of the tank would be at that moment. Since one should be able to access the instantaneous data for $\ddot{X}_4$, $\dot{X}_4$ and X_4 from Orcaflex (as well as for sway and yaw), then the equation of motion for the tank could be arranged as:

$$a_{\tau\tau}\ddot{\tau} + b_{\tau\tau}\dot{\tau} + c_{\tau\tau}\tau = -(a_{\tau 4}\ddot{x_4} + c_{\tau 4}x_4 + a_{\tau 2}\ddot{x_2} + a_{\tau 6}\ddot{x_6}) \qquad (6)$$

Where $\ddot{x_2}$ and $\ddot{x_6}$ are inertial contributions from sway and yaw from the 6DOF solution. Since the a/b/c coefficients are known, and the position/velocity/acceleration components are retrieved from the Orcaflex time history, the ship contribution to the equation of motion for the tank can be considered as a value C

$$C(t) = a_{\tau 4}\ddot{x_4} + c_{\tau 4}x_4 + a_{\tau 2}\ddot{x_2} + a_{\tau 6}\ddot{x_6} \qquad (7)$$

The equation of motion of the tank is solved using the aforementioned Finite Difference Method for a single time step at the current time t_n. The position and velocity data calculated for t_n is registered and then used in the next time step as the initial conditions. The position component of the tank, τ is used to calculate the applied force.

The applied force is a function of the tank angle. When the liquid is displaced to one side, the tank angle changes, and can be used to calculate the height the water has reached in the column.

$$\frac{w \tan \tau}{2} = h_z \tag{8}$$

Where $h_z = h_r - h_d/2$, or the height of the water in the column, and x_t is the tank transversal width.

$$F_{\tau>0} = \rho \frac{w \tan \tau}{2} w_r x_t g \qquad \text{kN} \tag{9}$$

0.5 Results and Analysis

A selection of results and analysis are presented for the Squatina without Skirt model. The scales have been edited out to ensure confidentiality.

Table 2: SQUATINA without Skirt: Floater Parameters

Variable	Value	Units
M_{ss}	17000	[tonnes]
V	16585	[m^3]
T_{Draft}	9.1	[m]
KB	4.55	[m]
H_{Deck}	12	[m]
KG	14.61	[m]
GM	25.47	[m]

Table 3: SQUATINA without Skirt: Tank Parameters

Variable	Value	Units
Case	(5,5)	[-]
h_{tank}	12	[m]
h_r	6	[m]
x_t	10	[m]
w	33.4	[m]
w_r	6	[m]
h_d	2.1667	[m]
m_{tank}	1206.7	[tonnes]
$\%_{weight}$	8.7	%
L	39.4	[m]
w_d	27.4	[m]
r_d	14.61	[m]
x_b	0	[m]
T_{tank}	14.5	[s]
τ_{max}	.2863	[rad]
	16.4049	[degrees]

0.5.1 Sensitivity Studies

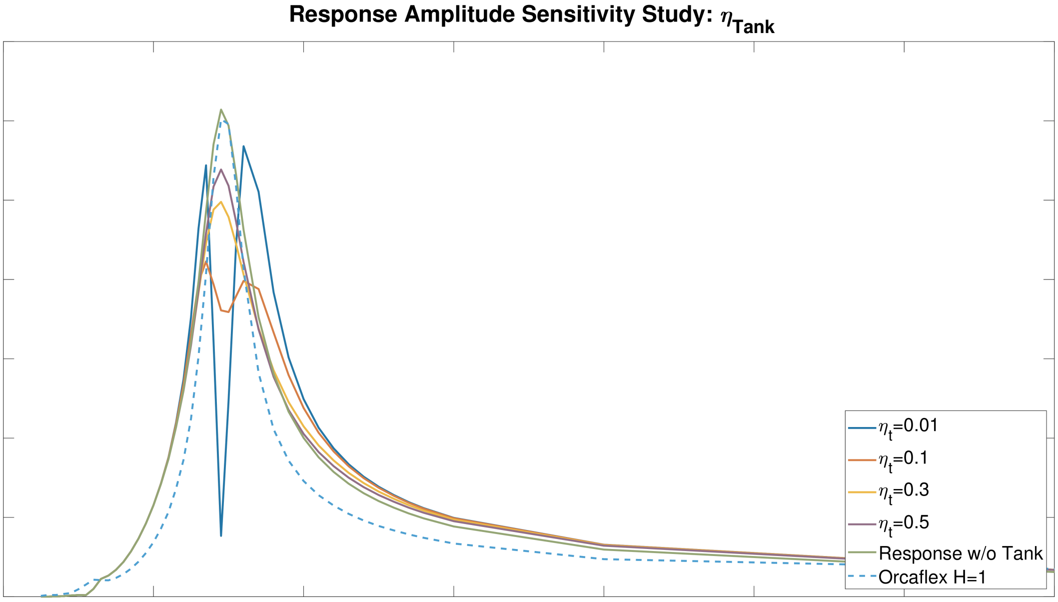
Response Amplitude Sensitivity Study: η_{Tank}

Figure 2: SQUATINA without Skirt: Response Amplitude Sensitivity Study for η_{tank}

The tank internal damping depends on the smoothness of the tank walls and the structural requirements (the presence of baffles, sharp corners, expanding or contracting channels). With a very smooth internal damping (η_t=0.01), the floater experiences a perfect anti-resonance at the resonant period. This means that there is perfect absorption of the roll motion by the tank. [32]. However, it is replaced by two new resonant peaks. According to Gawad et. al, optimal performance is achieved when the magnitudes of the two peaks are reduced to be approximately equal or leavel to each other at the structural resonant period. This ensures an acceptable response amplitude for the whole range of encounter frequencies. This suggests that there is an optimal damping for a given tank, which can be induced by artificial roughness, vortex generators, and baffles. [32].

0.5.2 Frequency Domain Response

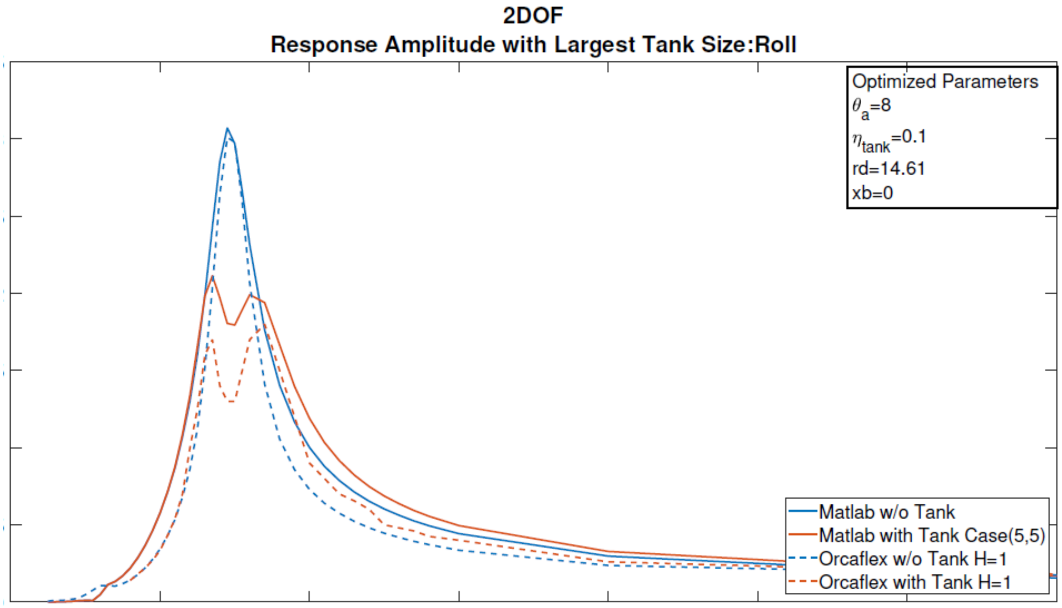

Figure 3: SQUATINA without Skirt: 2DOF Frequency Domain Response, $H_{wave} = 1$

0.5.3 Time Domain Response: Harmonic Excitation at Resonance

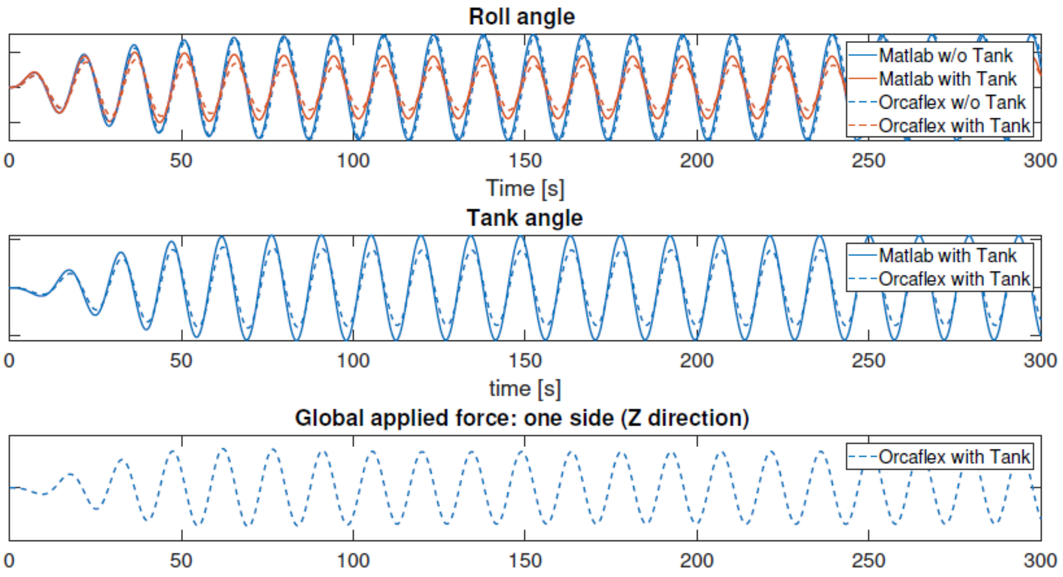

Figure 4: SQUATINA without Skirt: 2DOF Time Domain Response, Harmonic Excitation at T=14.5 [s] and H_{wave}=1 [m]

0.5.4 Irregular Waves

Comparison: Extreme Case 2, $\gamma = 5$

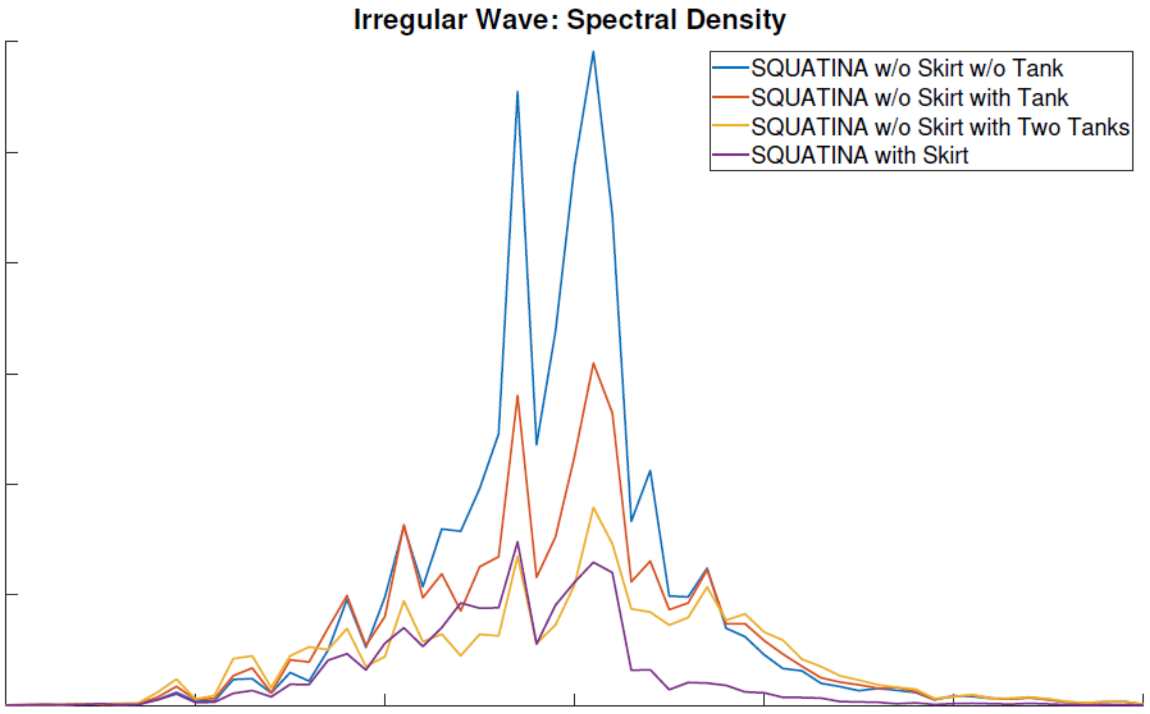

Figure 5: Comparison: Spectral Density for Extreme Case 2: $\gamma = 5$

Extreme Case 2 with $\gamma = 5$ has the most extreme peak responses of all the trial cases. The two-tank system exceeds the skirt model by a narrow margin around the resonance frequency

.07 Hz, as well as having notably higher responses between .075 and .08 Hz. This corresponds to the smaller period resonance peaks of the two-tank system.

The maximum roll amplitudes are again superior with the skirt system, with a 45% decrease in roll (over the two-tank system of 17%). The standard deviation values are closer, with a percent decrease of 44% for the skirt and 30% for the two tank system. For this case as well, the two tank model would only be recommended over the skirt model if sufficiently comparable responses, specifically with regards to the percent decrease in the standard deviation, were the driving principle.

Comparative Analysis: Irregular Waves

The most interesting result comes from the comparison between the SQUATINA without skirt without tank, SQUATINA without skirt with tank, SQUATINA without skirt with two tanks, and SQUATINA with skirt.

Extreme Cases For the Extreme Cases, the one-tank system underperforms the skirt system. The two-tank system has a maximum percent decrease in roll amplitude of 21%, compared to the skirt system with a roll reduction of 50%. The maximum percent decrease in standard deviation for the two tank system is 30%, and the maximum for the skirt system is 44%. *Therefore, the two-tank system underperforms the skirt system especially in extreme values of amplitude, but also in overall decrease of standard deviation.*

Storm Cases The Storm Cases were not calculated for the two-tank system, but the values can be extrapolated from its Extreme Case response. In the Extreme Cases, the two-tank system provides roughly 2x the percent decrease in roll amplitude and in standard deviation than the one-tank system. With this in mind, the maximum percent decrease in roll amplitude would be 40%, and the maximum percent decrease in standard deviation would be 42%. The maximum percent decrease in roll amplitude for the skirt system is 42%, and for the standard deviation is 48%. *This means that in the Storm Cases, a two-tank system would perform equally as well as a Heave Skirt.*

Optifloat The Optifloat model initially yielded positive results as well, with 40% decrease in roll amplitude in harmonic oscillation tests. However, in the irregular wave tests, the maximum percent decrease in standard deviation was only 4%. The Optifloat system might have been too well-damped initially to have warranted this investigation. An additional consideration is that the tank was not as long as the SQUATINA tank, and never reached saturation. *Overall, this performance is not recommended for installation.*