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Analysis of Motion on FPSO in Shallow Water with a Non-Collinear Environment

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ABSTRACT

The ship-shaped floating structures like FPSO has an ability to produce, storage and offloading the oil but it is does not have the drilling capability. Usually the FPSO in shallow water is connected with the single point mooring systems such as Vertical Anchor Leg Mooring (VALM) buoy systems. The objective of this paper is calculate the response amplitude operators (RAO) of spread moored FPSO with two mooring configuration and with the effect of non-collinear environment of wave and current. The analyses done by using ANSYS AQWA (version 14) software with runs two types of analysis which is hydrodynamics diffraction and hydrodynamics time response. The analysis also focuses to calculate the RAO and normalized hawser line force of FPSO and VALM systems. The result from the software has been compared with the experiment result to validate it. The different in meshing elements size also are taken into account. The analysis also focuses to compare the RAO between single leg mooring FPSO and spread moored FPSO with the same loading condition. From the analysis, the RAO for 4 mooring FPSO is higher compared than 8 mooring FPSO but the 8 mooring FPSO shows high value of cable forces than 4 mooring FPSO. It also shows the value of RAO of single leg mooring FPSO is higher compared to the spread moored FPSO.

KEY WORDS: *FPSO; VALM; ANSYS AQWA; Shallow Water.*

NOMENCLATURE

M_S	Structure mass
M_a	Added mass
B	Damping
C	Hydrostatics stiffness
F	Wave force (incident and diffracting forces)

1.0 INTRODUCTION

The development of the offshore industry commenced with the use of fixed structures. As development accelerated with the discovery of oil and gas in deeper water, the use of floating structure have become popular and commonplace. Among those floating structure is FPSO. This ship-shaped floating structures has an ability to produce, storage and offloading the oil but it is does not have the drilling capability.

Usually the FPSO in shallow water is connected with the single point mooring systems such as VALM buoy systems. Although the choosing of floating structure is always much better than conventional fixed structure, but in other way there are still have a problem. This is because in real condition, the FPSO will experience an excessive environmental force and non-collinear environment such as wind, waves and current which make the vessel in motion. Result from this motion towards the floating structures can reduce the operating level and affects the performance of the process performance.

Therefore, it is essential to analyze the effect of environmental force and non-collinear environment towards the motion and connection between the FPSO and VALM buoy system. In order to analyze the response amplitude operator for motion, there are some methods available. The common way which is always be performed to predict the FPSO motion by conducting the model test in towing tank. The same method is also applied to study the effect of wave run-up on bow and stern. Besides that, the other familiar method applied is using the ANSYS AQWA software.

2.0 HYDRODYNAMICS CHARACTER OF A FLOATING STRUCTURE

In general, the floating structure is assume rigid and undergoes six independent degrees of motion, in which three in translational and there in rotational. The translational or longitudinal motion consist surge, sway and heave motion while the rotational or angular motion consist pitch, roll and yaw motion. These six independent degrees of motion for ship-shaped floating structure could be seen in Figure 1.

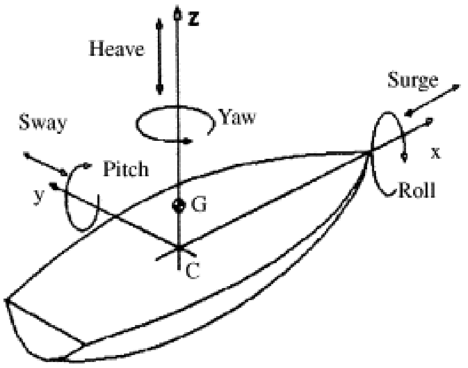

Figure.1: Free-floating body motions for ship-shaped structure

The simulation of floating structure dynamics problem can be performed by using three basic approaches which is a frequency domain analysis or time domain analysis or the combination between the frequency domain and time domain. The measurements of amplitude for the time domain and the frequency domain versus time can be illustrated in terms of graph as shown in Figure 2. Frequency domain analysis is an analysis that refers to a solution of the equation of motion by the methods of harmonic analysis of methods of Laplace and Fourier transforms while the time domain analysis usually utilizes the direct numerical integration of the motion equation in which it is allowing the inclusion of all systems nonlinearities.

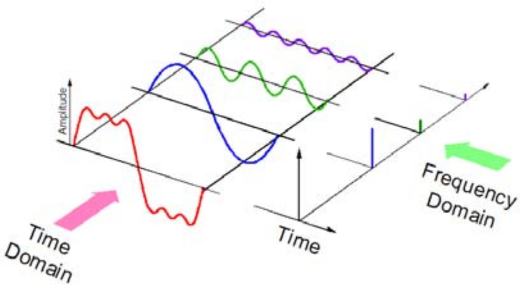

Figure.2: Time domain and frequency domain measurements.

3.0 RESPONSE AMPLITUDE OPERATORS (RAO)

The amplitude of the response of an offshore structure, fixed or floating, when subjected to a regular wave of given frequency can be normalized with respect to the amplitude of the wave. For a linear system, the normalized response is invariant with the wave amplitude at a wave frequency. If the normalized function is constructed for a range of wave frequencies of interest for a given offshore structure, and then the function is called as the Response Amplitude Operators (RAO) of Transfer Function. The RAO can be obtained either by theoretical or measured. The theoretical RAO can be obtained with the help of simplified mathematical formulas and when the problem is complicated to solve analytically or when the mathematical assumptions need verification, the measured process are performed on model of the prototype.

4.0 MOORING SYSTEM

Any mooring system is made of a number of lines (chain, wire or synthetic rope) with their upper ends attached to different points of the floating structure and their lower ends anchored at the sea bed. The cables are constructed from steel chain, rope or a combination of both. The ropes are available in constructions from steel and natural or synthetic fibers. The tension forces in the cables are dependent on the cable weight, its elastic properties and the mooring system. In a spread mooring system as multiple mooring legs are used to secure a vessel. This type of mooring is useful for securing permanently or semi permanently moored vessel.

5.0 THEORY AND METHODOLOGY

The response X of a structure in waves is calculated by solving the equation of motion in the frequency domain for unit wave amplitude. The formulas for the response of structure in waves are shown below:

$$\left[-\omega^2\left(M_s + M_a(\omega)\right) - i\omega B(\omega) + C\right]X(\omega) = F(\omega)$$

5.1 FPSO from Technical Paper

Table.1: FPSO data from technical paper

Principal Dimension	
Length	270.70 m
Breadth	44.30 m
Depth	21.70 m
Fully Loaded Draught	16.70 m
Displacement	172000 tonnes
Deadweight	140000 tonnes
Lightship	32000 tonnes
40 % of Deadweight	56000 tonnes
100 % of Deadweight	140000 tonnes

5.2 VALM Buoy without Skirt

Table.2: VALM buoy data

Principal Dimension	
Diameter	8.094 m
Height	3.70 m
Weight	81.2 tonnes
Draft	1.61 m
Deadweight	35000 tonnes

5.3 Design Environment

The extreme environment for mooring strength design is 100-year return storm and a 1-year return condition is the environment limitation for loading and offloading operation. This analysis will include the effect of wave and current towards motion, hawser line forces and the mooring forces with different loading condition [10]. The value for the wave height is based on the previous data that contain the value of wave height for every month in one year. This data was provided by Wan Aminullah Wan Abdul Aziz, (2012) [11].

Since the data shows different value of wave height, but the data that taken into account is the mean wave height for all over the month. For the current value, the value is decreased as it goes down towards sea bed, but at some region of sea, the current as much stronger at the middle compare to the surface and the bottom of the sea. For this study, the calculation for the distribution of current value as it goes down the sea bed are used the Couette Flow theory. In this theory, the flow between parallel plates with one plate fixed and the other is moving is similar to the sea surface with is moving and the surface of sea bed with is fixed [13].

Table.3: Data for wave height in Port Dickson

Location		**Port Dickson, N9**	
Coordinate		**2.5167 N**	**Latitude**
		101.8000 E	**Longitude**
Month	**Latitude**	**Longitude**	**Wave Height, H (m)**
1	2.5000	101.7500	0.881
2	2.5000	101.7500	0.862
3	2.5000	101.7500	0.940
4	2.5000	101.7500	0.905
5	2.5000	101.7500	0.884
6	2.5000	101.7500	0.898
7	2.5000	101.7500	0.811
8	2.5000	101.7500	0.914
9	2.5000	101.7500	0.919
10	2.5000	101.7500	0.941
11	2.5000	101.7500	0.936
12	2.5000	101.7500	0.912

Table.4: Design environment for FPSO simulation

Data Group		**Return Period**	
		1 - year	**100 - year**
Waves	Significant Wave Height	0.9 m	1.67 m
	Maximum Wave Height	0.941 m	1.74 m
	Peak Wave Period	8.7 s	11.8 s
	Direction	180° on the bow	
	Wave Speed	2.572 m/s	
Current	Surface Speed	1.03 m/s	1.77 m/s
	Middle Speed	0.81 m/s	1.43 m/s
	Bottom Speed	0.53 m/s	1.04 m/s
	Direction	135° starboard of bow	
Location Depth		69 m	

5.4 Non-Collinear Condition

The effect for the non-collinear is caused by the wave, current and wind towards the floating structure. This will affect the direction and movements of the floating structure. The collinear environment for the floating structure is caused by the combination of wave, wind and current move towards to floating structure in one direction only or is called as in-phase, which is move in one angle only. But in the non-collinear environment, the wind, wave and current move towards floating structure in different direction of angle. In this thesis, we only consider the effect of wave and current only since the wind thus not contribute a large effect towards floating structure. The non-collinear condition in the simulation are, the wave is heading 180° on the bow and the current is heading 135° starboard of the bow.

5.5 FPSO Principle Dimension

For this simulation analysis in ANSYS AQWA, the dimension of FPSO for two loading condition which is the ballasted condition (40% DWT) and fully loading condition (100% DWT) are taken into account. The dimension of the FPSO is taken from the TENAGA KELAS model.

Table.5: FPSO for fully loaded condition (100% DWT)

Particular	Value	Unit (SI)
Displacement	94041.27	Tonne
Volume	91747.58	m^3
Draft to Baseline	11.13	m
LWL	267.30	m
Beam wl	41.6	m
Cb	0.741	
LCB from zero pt	141.28	m
KB	5.91	m
BMt	12.94	m
BMl	457.55	m
GMt	18.85	m
KMt	18.85	m

Table.6: FPSO for ballasted condition (40% DWT)

Particular	Value	Unit (SI)
Displacement	46789.25	tonne
Volume	45648.05	m^3
Draft to Baseline	6	m
LWL	249.60	m
Beam wl	41.65	m
Cb	0.73	
LCB from zero pt	145.91	m
KB	3.18	m
BMt	23.34	m
BMl	731.62	m
GMt	26.52	m
KMt	26.52	m

5.6 Mooring Line Properties and Arrangement

For mooring line properties, this study used one types of mooring line which are chain mooring. It is estimated for this study to use minimum breaking load of 14955 kN. This value was referred and undergoes a little comparison based on previous study by Priyanto A. and Samudro (2006) [9], in which they suggested using chain diameter of 127 mm.

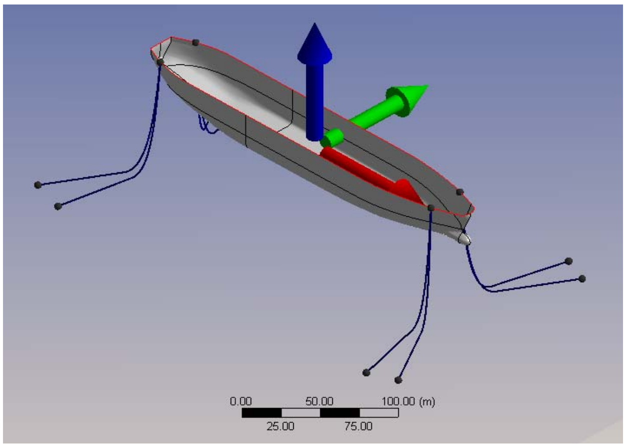

Figure.3: Configuration of 8 mooring FPSO

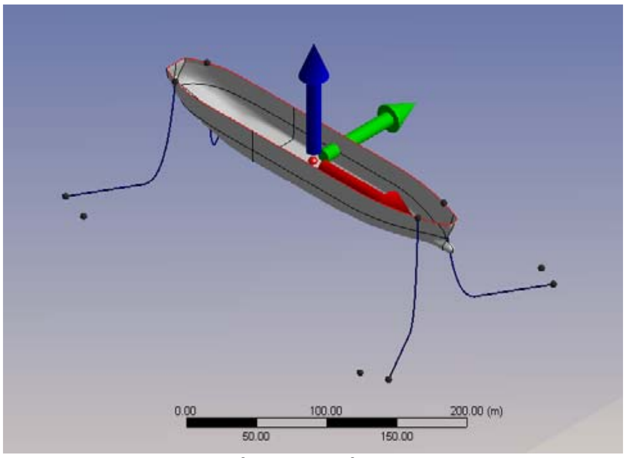

Figure.4: Configuration of 4 mooring FPSO

Table.7: Type of mooring chain used

Mooring Chain	Value	Unit
Offshore Mooring Chain		
Type : R4 - Stud Link Anchor Chain		
Breaking Load	14955	kN
Proof Load	11789	kN

5.7 Hawser Line Properties

The type of material for the hawser line used in this simulation is 3-strand nylon rope which is manufactured using premium grade, high tenacity and coated nylon fibers. This will resulted in a longer wearing, flexible and easy-to-handle rope, has greater strength and better abrasion resistance and ideal for uses requiring high-energy absorption. It is suitable for dock and anchor lines and also mooring lines.

Table.8: Hawser line properties

Hawser Line		Unit
Type	2" 3-Strand Nylon Rope - White	
Breaking Load for 1 Rope	376000	N
Breaking Load for 2 Rope	752000	N
Diameter Rope	48	mm
Minimum Breaking Strength	376	N
Safe Load	3.14	N
Stiffeners	5000	N/m
Weight	1.49	kg/m
length of hawser line, H_L	56.12	m
H_L / L_S	0.2	

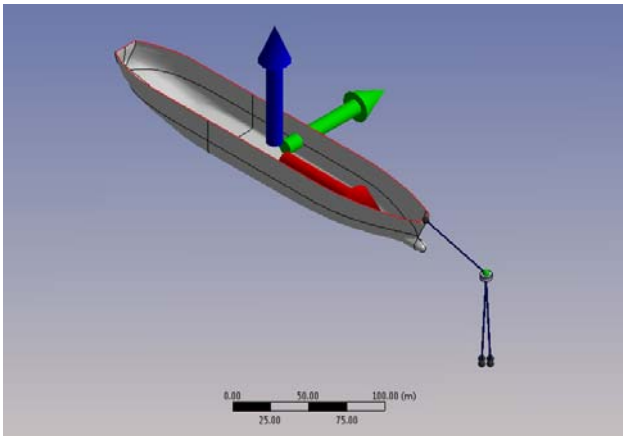

Figure.5: Connection of hawser line between FPSO and VALM buoy

5.8 Regular Wave Parameter

The type of regular wave that used is Airy Wave Theory. The value of frequency is depended on the analysis. In the FPSO and VALM system analysis, the range for frequency that used is between 0.061 Hz to 0.133 Hz with the steps of frequency of 0.004 Hz, while in the spread moored FPSO analysis, the range for frequency that used is between 0.039 Hz to 0.095 Hz with the steps of frequency of 0.004 Hz.

5.9 John F. Flory Coordinates Method

This method is use to determine the anchorage point for the mooring system and also the length of catenary mooring line. The locations of anchorage points need to be determining manually in the AQWA software since the software not automatically define the location. John F. Flory coordinate method is use because the calculation is simple and easy to understand. From John F. Flory, our aims is to obtain the value of X (m) = D_b (m) + D_t (m) and S (m) = D_b (m) + E_t (m).

For anchorage point, X is representing the distance between anchor and the fairlead and S is representing the curve distance between base point and the end point of chain attached to the ship. All the catenary mooring line used same value of pretension and this value of pretension is referred based on previous study by Priyanto A. and Samudro (2006) [9].

Table.9: Details of chain value

Input Value : Chain Properties		
Et	w	H
(m)	(kg/m)	(kg)
69	365.1	46700

Table.10: Value from John F. Flory and DM 26.5 method

DM 26.5 Method							John F. Flory	
C	T	V	S	X	Db	Dt	Q	Dt
(m)	(kg)	(kg)	(m)	(m)	(m)	(m)		(m)
128	71892	54659	149.7	128	81	47	1.9	47

6.0 RESULTS AND DISCUSSION

6.1 RAO for 100% Deadweight Loading Condition – Validation

The vessel motions with referring to the floating structure dynamics that consists six degree of freedom, three in translational motion, where surge, heave and sway in this motion and three in rotational motion, where pitching, rolling and yawing in this motion. But in this analysis, we only consider the surge, heave and pitch RAO for further analysis.All the result obtained was plotted as in Figure 6, Figure 7 and Figure 8.

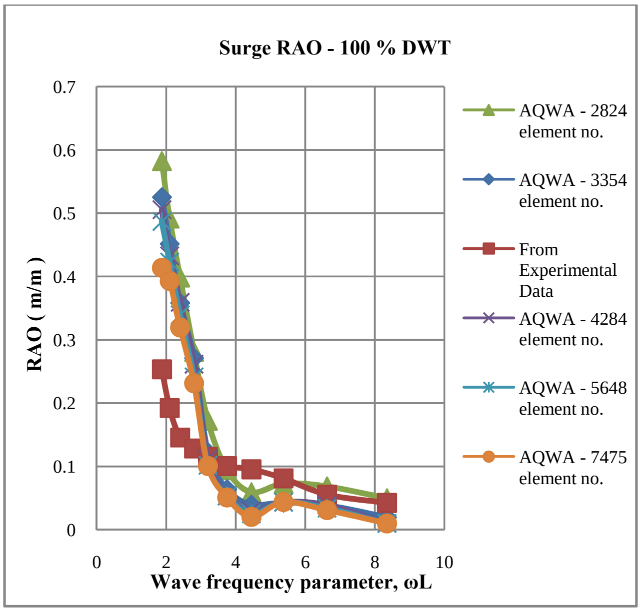

Figure.6: Graph of surge RAO versus wave frequency parameter

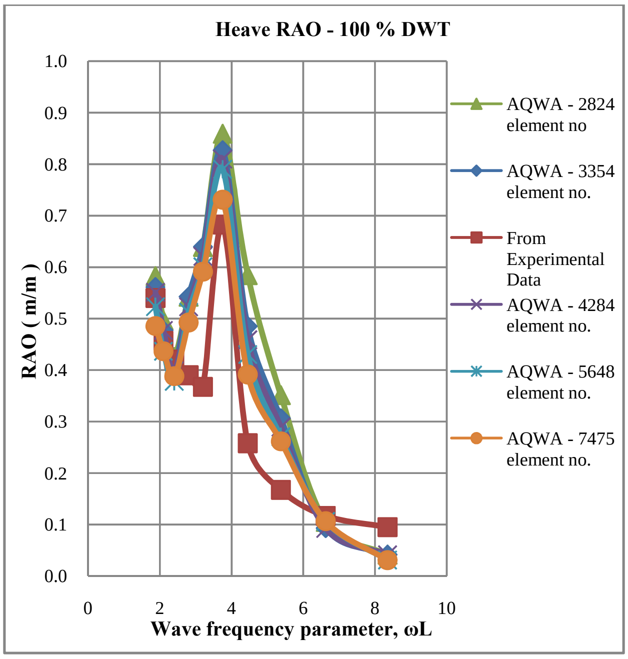

Figure.7: Graph of heave RAO versus wave frequency parameter

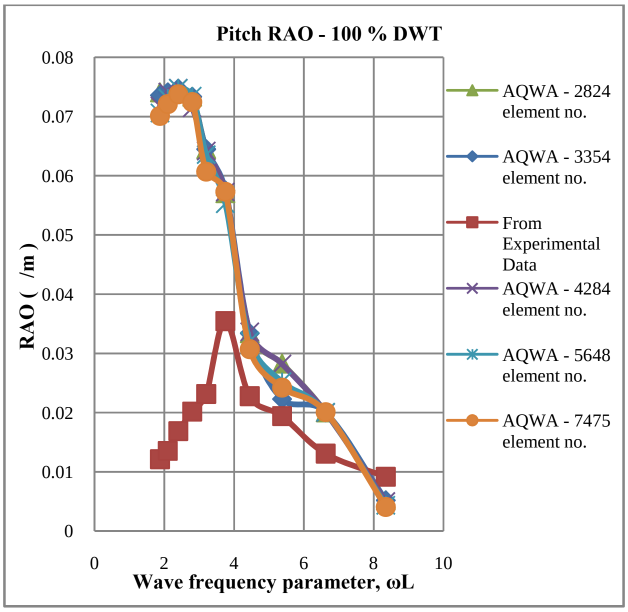

Figure.8: Graph of pitch RAO versus wave frequency parameter

For the surge RAO value obtained from simulation, the maximum value of RAO is 0.5255 m/m with the wave frequency parameter of 1.875 while the surge RAO from experimental data is 0.2536 m/m at the same value of wave frequency parameter. From this value, it show that, the value from experimental shows a lower value as compare to the value obtained from simulation. For the heave RAO value obtained from simulation, the maximum value of RAO is 0.8269 m/m at the wave frequency parameter of 3.75 while the heave RAO from experimental data is 0.6825 m/m at the same value of wave frequency parameter. For pitch RAO value obtained from simulation, the maximum value of RAO is 0.0747 degree/m with the wave frequency parameter of 2.4 while the pitch RAO from experimental data is 0.0354 with the wave frequency parameter of 3.75.

From this value obtained, it shows that the value from simulation by using AQWA indicated the higher value for three types of motions as compared to the value form experimental data provided by technical paper. This is because, there are some different in sizing of model between the model used in simulation and model used in experiment. Although, the value of differences is small, but it still contribute the value of vessel motions.

6.2 RAO for 40% Deadweight Loading Condition – Validation

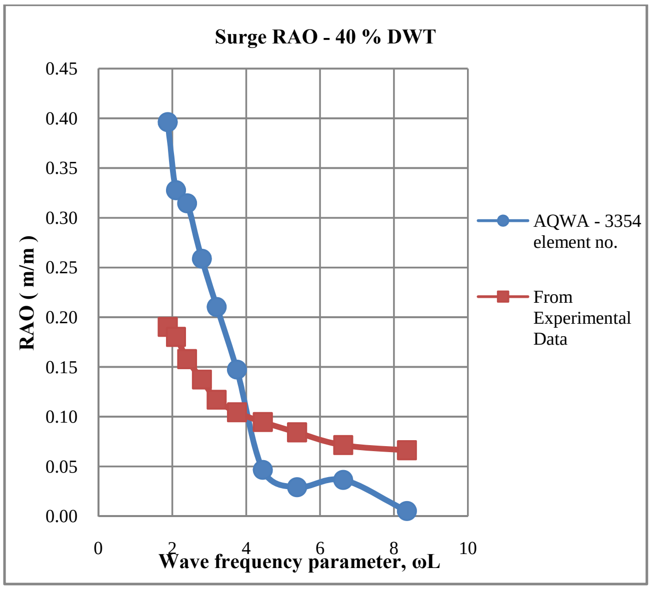

Figure.9: Graph of surge RAO versus wave frequency parameter

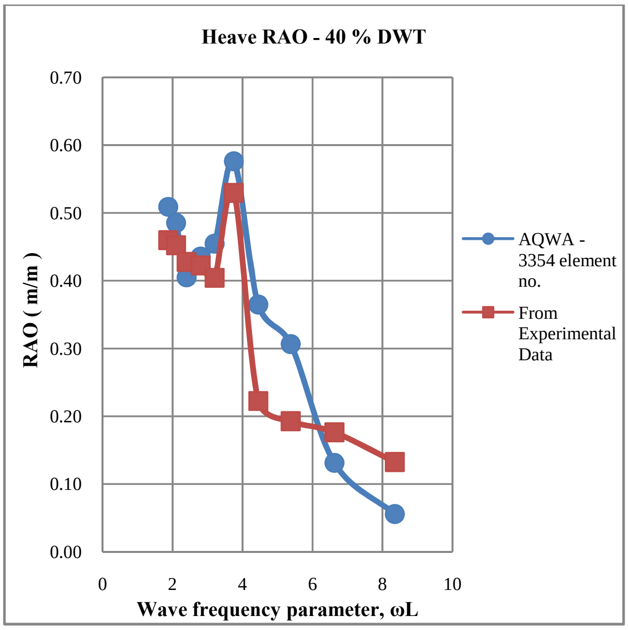

Figure.10: Graph of heave RAO versus wave frequency parameter

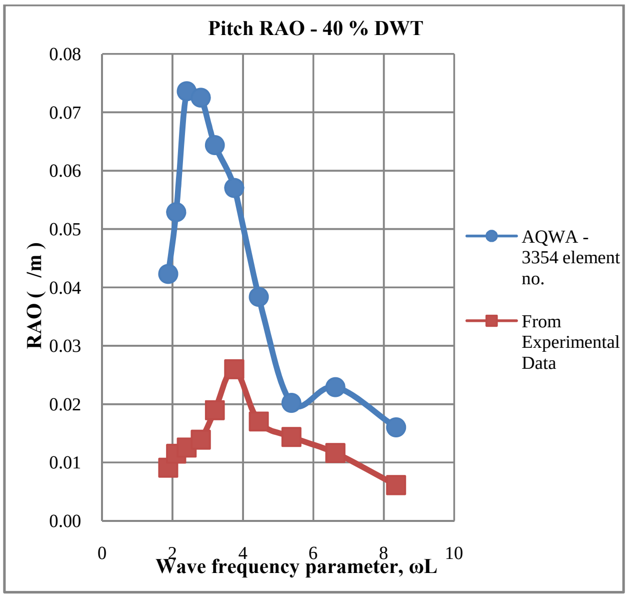

Figure.11: Graph of pitch RAO versus wave frequency parameter

For the surge RAO value obtained from simulation, the maximum value of RAO is 0.3961 m/m with the wave frequency parameter of 1.875 while the surge RAO from experimental data is 0.1903 m/m at the same value of wave frequency parameter. From this value, it show that, the value from experimental shows a lower value as compare to the value obtained from simulation. For the heave RAO value obtained from simulation, the maximum value of RAO is 0.5762 m/m at the wave frequency parameter of 3.75 while the heave RAO from experimental data is 0.5296 m/m at the same value of wave frequency parameter. For pitch RAO value obtained from simulation, the maximum value of RAO is 0.0736 degree/m with the wave frequency parameter of 2.4 while the pitch RAO from experimental data is 0.02598 with the wave frequency parameter of 3.75.

From this value obtained, it shows that the value from simulation by using AQWA indicated the higher value for three types of motions as compared to the value form experimental data provided by technical paper. This is because, there are some different in sizing of model between the model used in simulation and model used in experiment. Although, the value of differences is small, but it still contribute the value of vessel motions.

6.3 Normalized Hawser Line Force For 40% And 100% Deadweight

The value of normalized hawser line is obtained when the hawser line force (N) is divided with the breaking load of the nylon rope that used to connect the FPSO and VALM buoy. This breaking load of nylon is choosing based on the diameter of nylon used and also the length of nylon rope.

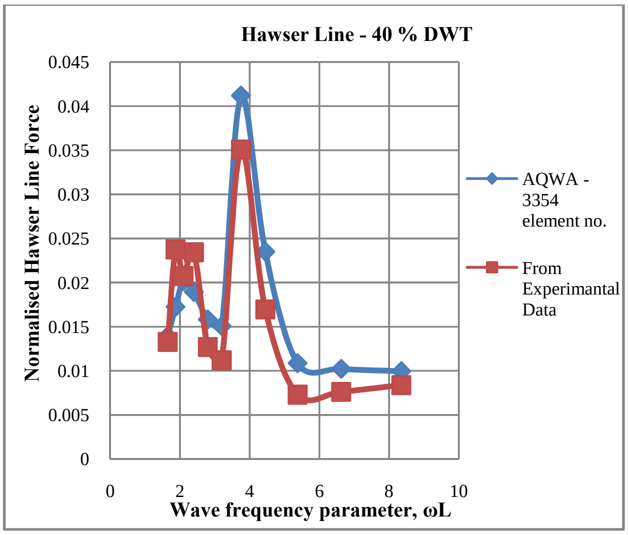

Figure.12: Graph of hawser line force for 40% DWT

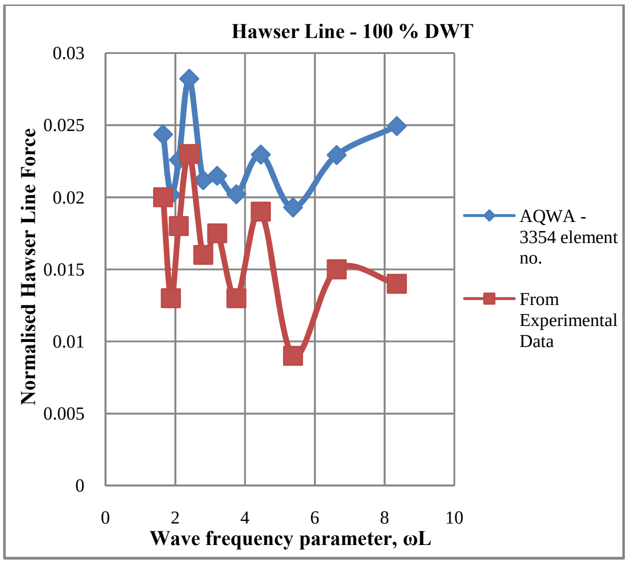

Figure.13: Graph of hawser line force for 100% DWT

In simulation, the maximum value of hawser line force for 40 % of deadweight is occurred at the wave frequency parameter of 3.75 with a value of 30983.31 N while the maximum value of hawser line force for 100 % of deadweight is occurred at the wave frequency parameter of 2.4 with the value of 21222.02 N. From the graph plotted, it shows that the value of normalized hawser line forces are bigger in 40 % of deadweight loading condition as compare to 100 % of deadweight loading condition. This is because, when the draft of FPSO is change from lower to higher draft, the value of maximum hawser line force is decrease. In fully loaded condition, the draft will be 11.13 m and the connection between the VALM buoy and FPSO will become almost in level but when the FPSO in ballasted condition which is the draft of FPSO is 6 m, the nylon rope will be in tension condition since position of connection of FPSO to VALM buoy is increase. Thus, it will make the nylon rope became more slighted as compare to the condition of nylon rope in fully loaded condition.

6.4 RAO of Spread Moored FPSO

In this case study, the FPSO will be moored with two configuration of mooring that attached at the bow and stern of vessel. The configuration of mooring for FPSO is four mooring type, two at starboard side and two at port side while another configuration of mooring consists eight mooring type, four at starboard side and four at port side. In this case study, the effect of non collinear environment will take into account. The direction of wave is 180° of bow with the wave speed of 2.572 m/s and current is 135° starboard of bow with the current speed of 1.0288 m/s. The current speed is variable and it is depend on the depth of sea. The current speed a maximum at sea surface but the current speed a minimum at sea floor.

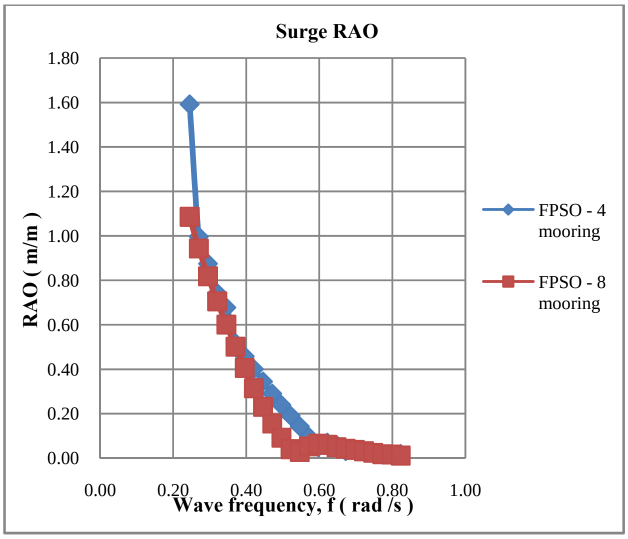

Figure.14: Graph of surge RAO versus wave frequency for spread moored FPSO

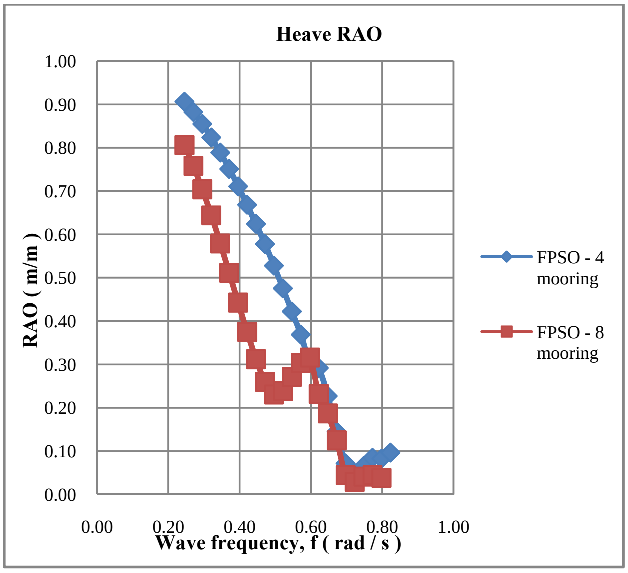

Figure.15: Graph of heave RAO versus wave frequency for spread moored FPSO

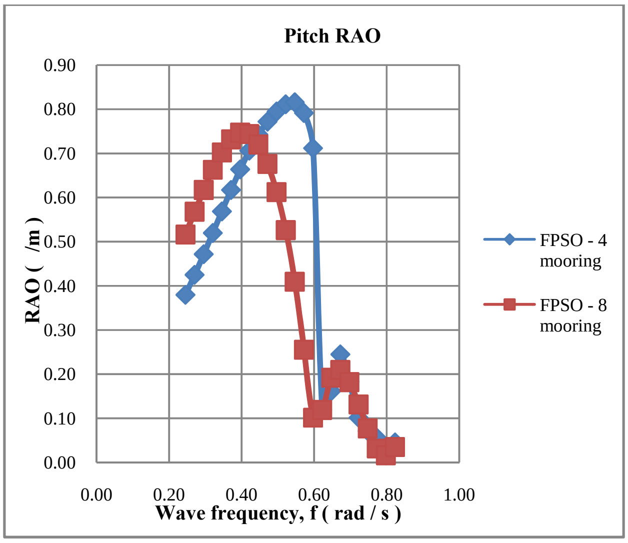

Figure.16: Graph of pitch RAO versus wave frequency for spread moored FPSO

From the graph, the 4 mooring FPSO shows the higher value for vessel motions in surge, heave and pitch as compare to the 8 mooring FPSO. The maximum value for the 4 mooring FPSO in surge RAO is 1.5921 m/m while the maximum value of 8 mooring FPSO is 1.0856 m/m. The maximum value of heave RAO for 4 mooring FPSO is 0.9063 m/m while the maximum value of heave RAO for 8 mooring FPSO is 0.8060 m/m. In pitch RAO, the 4 mooring FPSO result a higher value which is 0.8158 degree/m as compare to the value for 8 mooring FPSO which is 0.7468 degree/m. The value of vessel motion is higher as compare to the value obtained from 8 mooring FPSO is because, the 4 mooring FPSO only have a 4 mooring cable in order to hold the FPSO in fixed position as compare to the 8 mooring FPSO in which have 8 mooring cable that hold FPSO tightly in position.

6.5 Cable Force of Spread Moored FPSO

In spread moored FPSO analysis, the mooring cable will experience the static and dynamics force cause by the environmental forces. The function of mooring cable is to hold the FPSO from excessive movement in six degree of freedom when the environmental forces like wave, wind and current acting on it. But this will depend on how many mooring cable attached at the FPSO. When the number of mooring cable is increase, the vessel motion will be less but the cable force will be higher. This cable forces is different for every value of frequency.

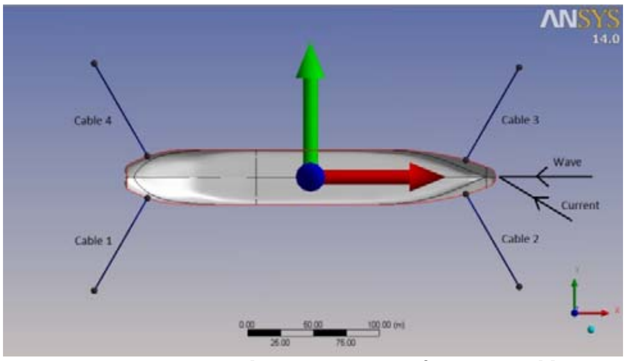

Figure.17: FPSO with 4 arrangement of mooring cable

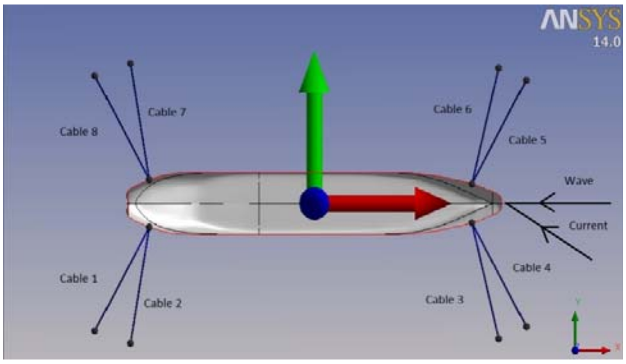

Figure.18: FPSO with 8 arrangement of mooring cable

Table.11: Cable force of chain mooring for 4 mooring FPSO

Frequency (Hz)	Chain - Cable Forces For FPSO - 4 Mooring			
	Cable 1 (N)	Cable 2 (N)	Cable 3 (N)	Cable 4 (N)
	Starboard Side		Port Side	
0.025	11953105	17327198	16551543	11937983
0.05	17730506	13889143	15128032	12403196
0.075	10356188	13452469	15577817	12652067
0.1	8422611	12729248	15416175	11020308
0.125	21285238	11170431	14213361	8867799
0.15	24333784	10171959	13435648	7385428.5

Table.12: Cable force of chain mooring for 8 mooring FPSO

Frequency (Hz)	Chain - Cable Forces For FPSO - 8 Mooring			
	Cable 1 (N)	Cable 4 (N)	Cable 5 (N)	Cable 8 (N)
	Starboard Side		Port side	
0.025	12172053	17828660	17410564	12060437
0.05	10954303	16232192	15701852	60790772
0.075	35818352	15338333	14064365	11769851
0.1	9197361	13343838	15822679	11874359
0.125	29418874	12342488	15071999	10683999
0.15	32685306	11160960	14235631	9085992

On the same condition, the cable forces for FPSO 8 mooring experiences the higher value of cable forces as compare to the FPSO 4 mooring with the same position of mooring chain. Other than that is, when the value of frequency is higher, the value of cable forces also increased. Even though the value of cable forces is higher, but the mooring chain can still operates under safety condition because the value of the cable forces still not exceed the value of breaking load of mooring chain.

6.6 Comparison of RAO between Spread Moored FPSO and Single Leg Mooring FPSO

For this analysis, the condition for both type of FPSO is based on the fully loaded condition with 100 % deadweight. The simulation only takes the wave effect as the environmental effect towards FPSO. The direction of the wave stills the same as the previous simulation, which is the 180° bow of vessel. The analysis of RAO only focusing on the heave, surge and pitch RAO but the hawser line forces for single leg mooring FPSO and cable mooring forces for spread moored FPSO are not be discussed.

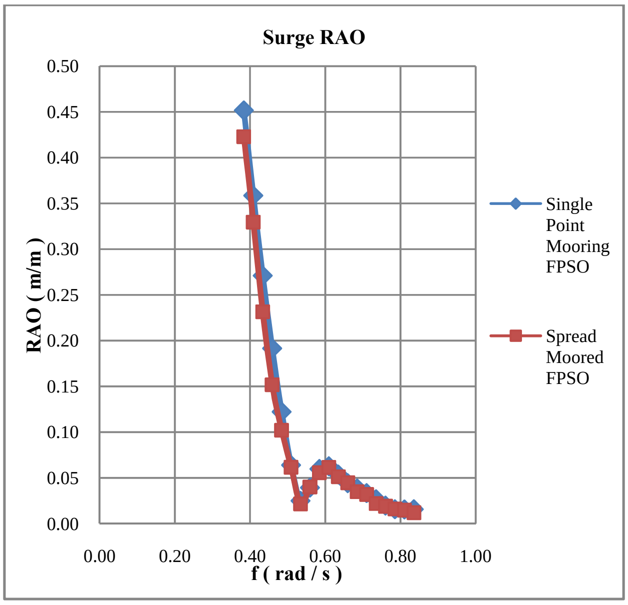

Figure.17: The value of surge RAO for both types FPSO

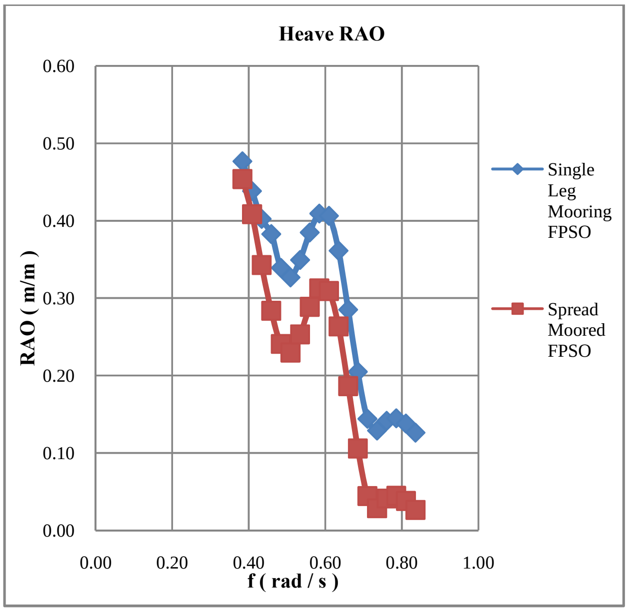

Figure.18: The value of heave RAO for both types FPSO

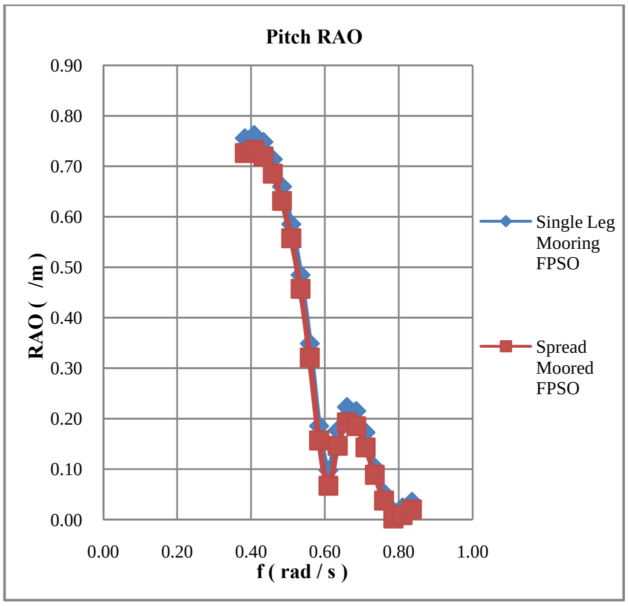

Figure.19: The value of pitch RAO for both types FPSO

The surge RAO for single leg mooring of FPSO shows the higher value compare to the value of surge RAO of spread moored FPSO. Even though the value of surge RAO between this two FPSO shows the a little different but it can give the impact the operation of FPSO itself. In shallow water area, the dynamics of floating structure is very crucial and need very detail analysis since it dealing with the possibility of changing in the environmental condition. For the value of heave RAO, single leg mooring FPSO shows the higher as compare to the value of spread moored FPSO. This is because, in the single leg mooring FPSO, there is no mooring is attached at the FPSO while in the spread moored FPSO, there are mooring attached on it. Since the function of the mooring is to restrict the motion of vessel, the spread moored produce the lower value of heave RAO as compared to the single leg mooring FPSO although in the same loaded condition. The value of pitch RAO for the single leg mooring FPSO shows the higher value as compare to the spread moored FPSO but the differences between this two FPSO are not too large. The conclusion is the single leg mooring FPSO produce the higher value of RAO for surge, heave and pitch as compared to the spread moored FPSO.

7.0 CONCLUSIONS

Based on the result and analysis of the study, the conclusions are obtained from this study as follows:

- The result of response amplitude operators obtained from the simulation between FPSO and VALM systems which using ANSYS AQWA were compared with the experimental data provided by the previous research paper.From the value obtained, it shows that the value from simulation by using AQWA indicated the higher value for three types of motions as compared to the value form experimental data provided by technical paper. This is because, there are some different in sizing of model between the model used in simulation and model used in experiment. Although, the value of differences is small, but it still contribute the value of vessel motions.
- The result of hawser line force from simulation also were compared with the experimental data provide.In fully loaded condition, the draft will be 11.13 m and the connection between the VALM buoy and FPSO will become almost in level but when the FPSO in ballasted condition which is the draft of FPSO is 6 m, the nylon rope will be in tension condition since position of connection of FPSO to VALM buoy is increase. Thus, it will make the nylon rope became more slighted as compare to the condition of nylon rope in fully loaded condition.
- The FSPO that have a higher number of mooring chains produce the smaller value of RAO but produce the higher value of cable forces with the same condition. In this analysis, only the value of dynamics cable forces which produce from simulation is taken into account and the static cable forces is assume as zero.
- The single leg mooring FPSO produce the higher value of RAO for surge, heave and pitch as compared to the spread moored FPSO at the same loading condition.

We can conclude that, the vessel motion especially the FPSO in shallow water is affected by the non collinear environment such as wave and current.

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