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Effect of Wave Steepness on Yaw Motions of a Weathervaning Floating Platform

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Abstract

Experimental studies were carried out at the Institute for Ocean Technology, Canada, in collaboration with UWA to assess the response of a 1:60 scaled Floating Production Storage and Offloading (FPSO) model in complex sea states. The model was moored by means of four instrumented mooring lines attached to an internal turret. As part of these experiments a series of model tests in regular waves were conducted. Numerical computations for linear motion response of the FPSO were conducted using well established boundary element packages. It is found that the model deviated significantly from linear behaviour in cases where there were involuntary heading changes. These changes were further understood by looking at the phasing between surge and sway accelerations.

Introduction

The quest for energy has been foremost for many national governments. Sources for Oil, currently satisfying 38% of world's energy requirements [Source IEA/World Energy Outlook], have been depleting onshore, and to keep up with the demand, exploration & production companies have had to seek into farther and deeper waters offshore. Floating Production Storage and Offloading (FPSO) vessels, which are ship-shaped floating structures, are deployed for oil and gas production in these waters. A FPSO is maintained at station by a set of mooring lines. These moorings are connected to a turret, which acts as a swivel arrangement for the vessel. Turrets can be positioned externally or internally with respect to the vessel. The turret allows the vessel to weathervane, to station the vessel heading facing the dominating environmental force. This is a passive arrangement, which at times can be assisted actively using dynamic thrusters. The ability of a vessel to weathervane on its own, without any assistance of these dynamic thrusters is dependent upon the prevailing sea conditions. Non-linear drift loads, and complex sea states with wind, sea, swell and current arriving in different directions influence the heading of the vessel. Young [1] observed a lack of correlation between wind-driven seas and long period swells in cyclonic environments. These lead to questions on the probable direction to which the vessel shall align itself. It is conventionally assumed that the vessel will align with the most dominant load direction, along with continuous yaw motion. Brown and Liu [2] have discussed on the calming effect of yaw (heading) motion by prevailing wind conditions. Paton et al. [3] have discussed large unstable sway-yaw motions affecting the natural weathervaning capabilities of the vessel. Another significant effect on weathervaning could be the roll motion, which is affected by the sway-yaw coupling. Martijn et. al. [4] discuss the sway-yaw motions, which tends to narrow and reduce the roll response peak. All these studies point to the importance and complex nature of yaw motion.

It is standard practice in offshore engineering to conduct linear frequency domain analysis using boundary element (panel method) packages. This analysis is accurate for small waves, where the response is proportional to the wave height. Conducting such analyses serves two purposes: 1. It provides a baseline linear comparison, and 2. The hydrodynamic coefficients as functions of frequency are obtained which may then be used in more complex time domain analyses.

Any free-floating body's response to a wave spectrum in a particular heading direction can be characterised by its motions and rotations along the three Cartesian axes. The governing equations for the rigid body motions of a body are:

$$\left(M_{ij} + a_{ij}\right)\ddot{x}_j + b_{ij}\dot{x}_j + k_{ij}x_j = F_i(\theta, t), \qquad (1)$$

where

M_{ij} = Oscillating mass/ moment of inertia
a_{ij} = Added mass/ moment of inertia
b_{ij} = Damping (hydrodynamic, structural, mooring etc.)
k_{ij} = Restoring stiffness (hydrostatic and mooring)
F_i = Exciting forces in the i^{th} direction, along direction θ, see Fig. 1.
$x_j, \dot{x}_j, \ddot{x}_j$ = the displacement, velocity and acceleration of the vessel in the j^{th} direction
i, j = 1, .. 6, denote the six degrees of freedom surge, sway, heave, roll pitch and yaw.

For a wave of the form A cos(ωt), the solution of (1) is of the form,

$$x_i(t) = x_{0i}\cos\left(\omega t + \alpha\right) \qquad (2)$$

The amplitude of these responses can be described using the Response Amplitude Operators (RAO). RAO is defined as the ratio of the magnitude of response to the amplitude of the incident wave.

$$\left|RAO_i\right| = \frac{x_{0i}}{A} \qquad (3)$$

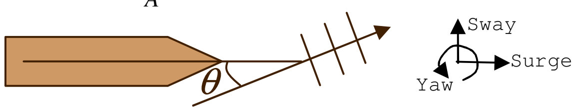

Figure 1: Coordinate system for heading angle

RAOs are applicable for any oscillatory loads experiencing linear responses. The integral features of an RAO are its scalability and superimposition properties. The RAO is dependent upon the physical characteristics and orientation (i.e. heading) of the vessel with respect to oncoming waves. Thus as the mean heading of a vessel changes due to yaw drift, its RAOs will also change. The present study is focused on response of FPSO in

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complex, bi-directional and bi-modal seastates. In addition to that, we were also interested in long waves and ability of a FPSO to maintain its course in such seastates. We present here, our findings on FPSO heading changes and motion response in long regular waves.

Experimental Program

Test facility

The tests were conducted at the Ocean Basin, Institute of Ocean Technology, National Research Council, Canada. The basin dimensions are 75 m x 32 m and the water depth was set at 2.8 m. This basin was equipped with 188 wave-maker panels on two walls (south & west). The other two walls of the basin were equipped with an array of nets for passive wave dissipation in order to avoid unwanted reflections. Regular waves were generated at the west wall. Wave gauges were positioned as shown in Figure 2.

Prior to installing the model in the basin, all the sea states were run with an array of wave probes in place of the model (apart from those shown in Figure 2) for wave matching.

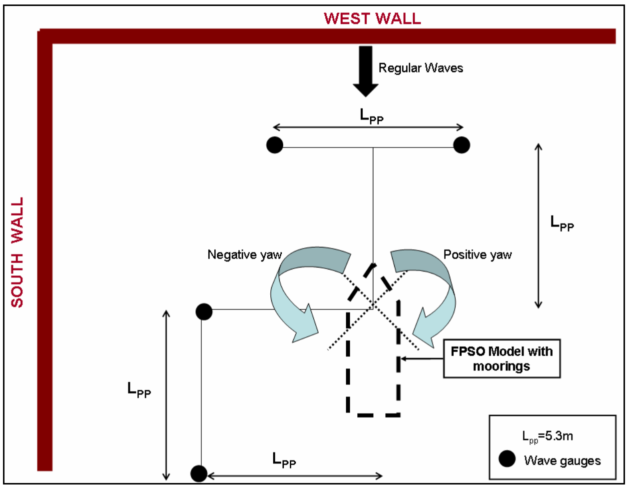

Figure 2: Test Basin

Model set up

A generic FPSO hull was modelled at with scale ratio, 1 in 60. Details of the model are given in Table 1. The model was positioned at station with the aid of four mooring lines connected to the turntable at the bottom of the internal turret. The mooring lines were at 90° separation. The model was free to weathervane about the turret. The model was equipped with two different systems for measuring its motions. The well-known optical tracking system, Qualysis, was used to directly measure the motions, and an inertial system recorded the three linear accelerations and the three angular velocities.

Test Matrix

We consider response of the model in regular waves. A series of regular waves was initially run based on ITTC recommendations [5] of keeping the ratio of the wavelength to the wave amplitude (λ / H) constant. The first series of tests were run for a set of regular waves whose length was chosen from 0.5 L_{pp} to 2.0 L_{pp} , such that λ / H = 50 . The waves were run for a total time of 15 minutes intended as full scale time. It was observed that the vessel tended to yaw significantly. In order to better understand the stable heading over time, long runs (two hours full scale time) with regular waves with different initial headings have been performed. Details of the test matrix are given in Table 2.

Parameter	*Notation*	*Value*	*Unit*
Overall Length	L	5.3	m
Length between Perpindiculars	L_{pp}	5.849	m
Beam Width	W	0.954	m
Depth	d	0.470	m
Draft	d_f	0.176	m
Displacement	D	675	kg
Metacentric Height	GM	0.462	m
Vertical Centre of Gravity (VCG), above keel	VCG	0.284	m
Longitudinal Centre of Gravity (LCG), fore of aft perpendicular	LCG	2.873	m
Turret position, fore of aft perpendicular	LCG_T	1.100	m

Table 1: Model Details

Run No.	λ / H	H [m]	T [s]	λ [m]
1	50.000	0.071	1.504	3.533
2	25.000	0.159	1.596	3.975
3	15.000	0.265	1.596	3.975
4	93.337	0.088	2.298	8.245
5	93.337	0.088	2.298	8.245
6	93.337	0.088	2.298	8.245
7	50.000	0.071	1.504	3.533
8	25.000	0.159	1.596	3.975
9	15.000	0.265	1.596	3.975
10	93.337	0.088	2.298	8.245

Table 2: Test Matrix

Computational Model

Computational modelling of the FPSO was conducted using the boundary element program WADAM, available within the SESAM software package of Det Norske Veritas, Norway. A finite mesh structure was generated using the PREFEM module within SESAM as seen in Figure 3.

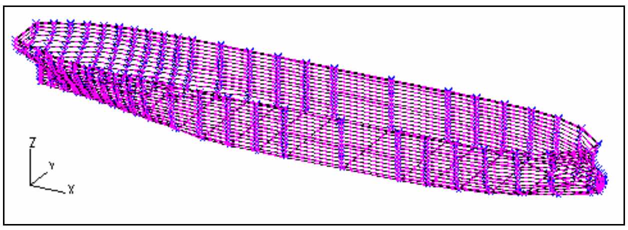

Figure 3: Computational model

The computational model was loaded with hydrostatic pressure on its outer surface. Since WADAM is a linear diffraction program, non-linear instabilities are not computed. By orienting the model at various headings, WADAM can provide the linear RAO experienced by the hull in these directions. These RAOs are for free bodies, without considering mooring. Mooring forces have little effect on vertical plane motions, as surge, sway & heave respond linearly with the wave height (Guedes Soares et. al. [6]).

Comparisons of results and discussions

The measured yaw response time histories of various runs from Table 2 are shown in Figure 4. For different λ/H, the characteristic of the yaw response was noted, as summarized in Table 3. From Table 3, it can be noted that wave steepness affects the weathervaning ability of the vessel. In addition, the effect of the wavelength becomes more prominent at low wave steepness.

From Figure 4 two distinct regions can be noted. In the initial transitional zone, the vessel is weathervaning and stable heading is not achieved. In the stabilized zone, the vessel heading is stable, and the vessel yaws about this heading. The RAO from model tests was determined separately for these two zones.

λ / H	Run Nos	Stabilized Heading	λ [m]
15.000	3, 9	No stable heading	3.533
25.000	2,8	52^o to 53^o	3.975
50.000	1,7	3^o to 4^o	3.975
93.337	4,5,6,10	42^o to 55^o	8.245

Table 3: Stabilized Heading angles for each test run

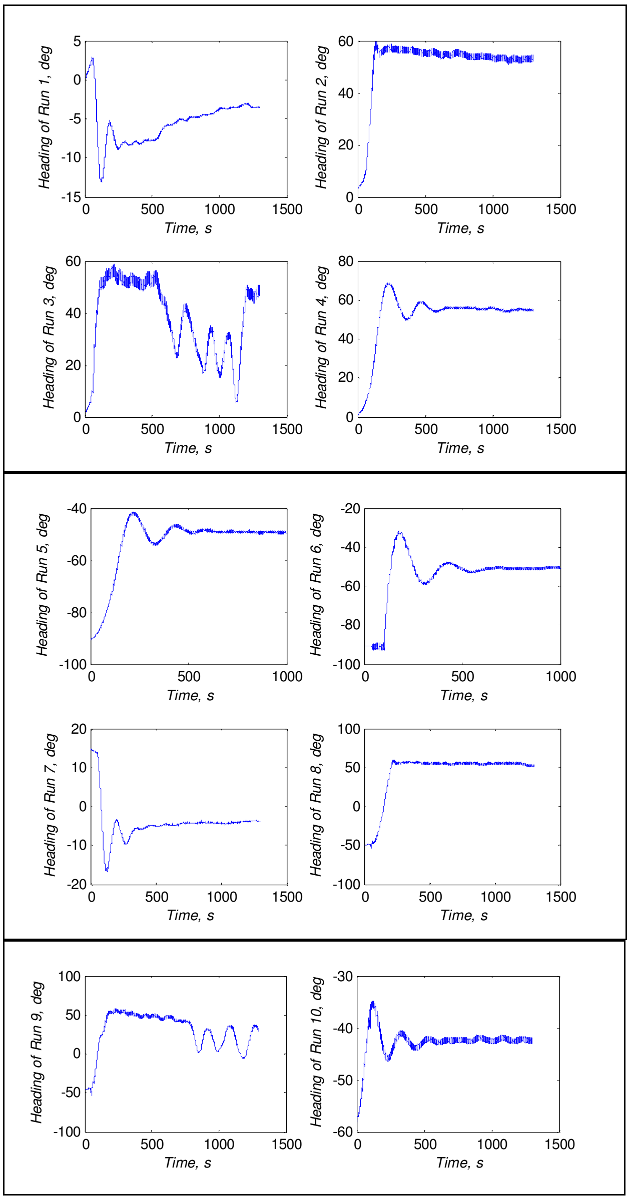

Figure 4: Heading vs. Time Plots for Runs of Table 2

The estimated RAO for all six motions are plotted alongside those generated by WADAM in Figures 5 – 10. Various curves denote results for various headings. Since the computational RAOs are obtained from a frequency domain analysis, significant deviations from them may be attributed to non-linear effects. From Figure 5 to Figure 10, it can be deduced that significant non-linear effects are present in surge and yaw motions, and in sway to a smaller extent. It is observed that as the wave steepness decreases, the spread of RAO values in the stabilised and transitional zone increases. At λ/H=93.33, the non-linear effects seem to be of same order as of λ/H=15.

The mean drift in yaw is primarily due to a balance between the drift forces in the horizontal plane. These forces in turn may be understood by examining the phasing between surge and sway accelerations. Figures 11 and 12 show phase plots of measured surge and sway accelerations for two cases of high and low heading. It is observed that for smaller heading angles (Figure 11) they are 90^o out-of-phase indicating a damping mechanism

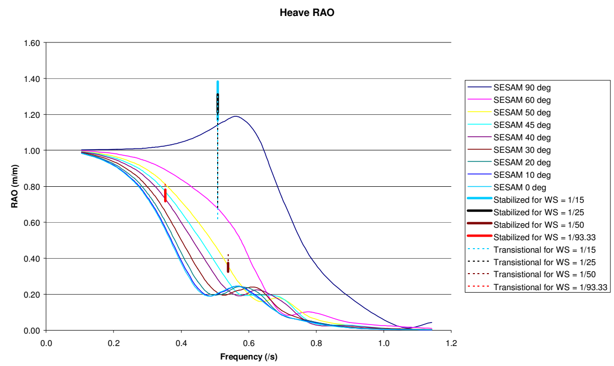

Figure 5: RAO in Heave vs. Incident Wave Frequency

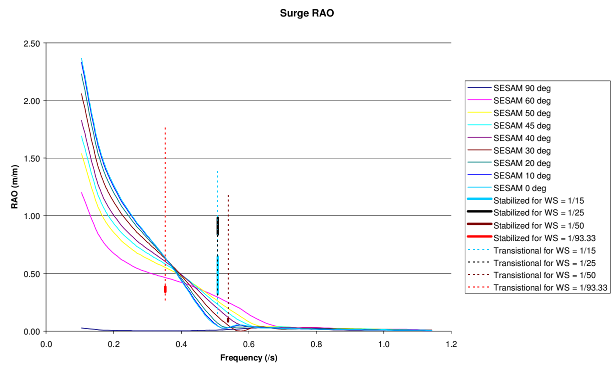

Figure 6: RAO in Surge vs. Incident Wave Frequency

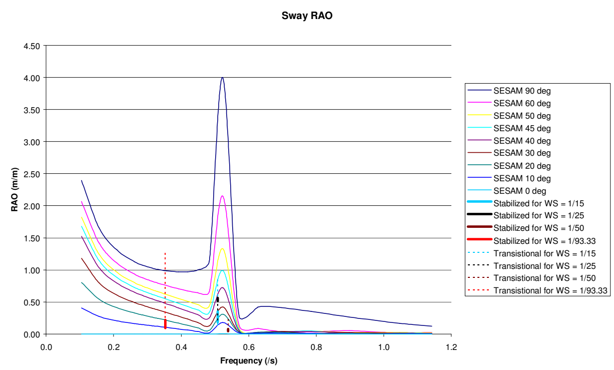

Figure 7: RAO in Sway vs. Incident Wave Frequency

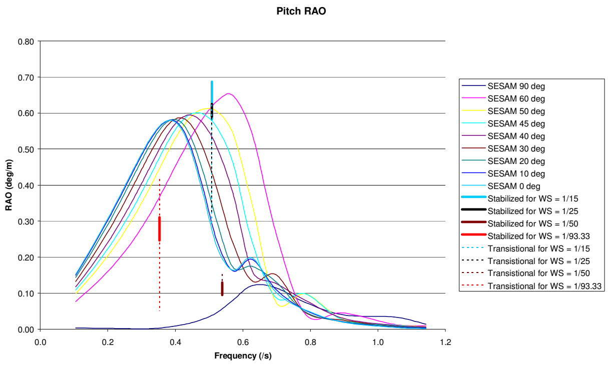

Figure 8: RAO in Pitch vs. Incident Wave Frequency

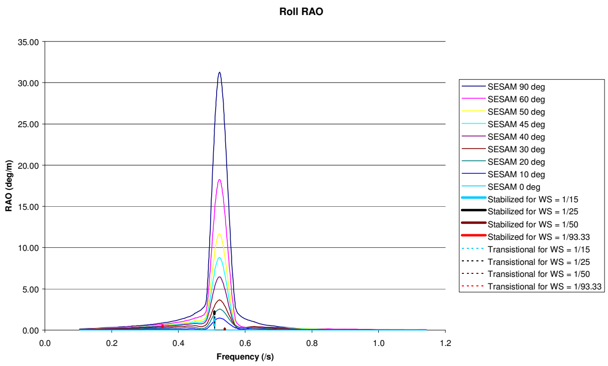

Figure 9: RAO in Roll vs. Incident Wave Frequency

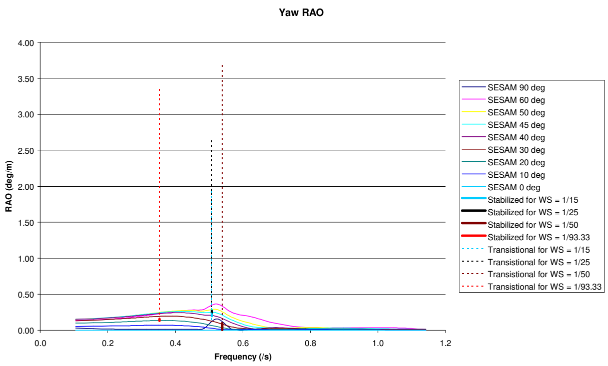

Figure 10: RAO in Yaw vs. Incident Wave Frequency

at play. At larger heading angles (Figure 12) the two accelerations are 180^{o} out-of-phase indicating an inertial coupling which may promote the drifting process.

Conclusions

Following conclusions were drawn based on the analysis of experimental and numerical data.

- Large yaw heading changes observed for lower wave steepness and large wavelengths.
- Linear response behaviour is observed for pitch, roll and heave motions, both in stabilized and transitional zones.
- Non-linear response is observed in the transitional zone, in surge and yaw motions, and to a lesser extent in sway.
- The non-linear response of the vessel in surge is further exemplified in its coupling with sway acceleration, wherein the damping nature of surge forces over sway forces and vice versa is reduced at higher wave steepness and wave lengths.

Study on examining the mooring line tensions, and simulation of time domain analyses to gain a better understanding of the weathervaning instability is under progress.

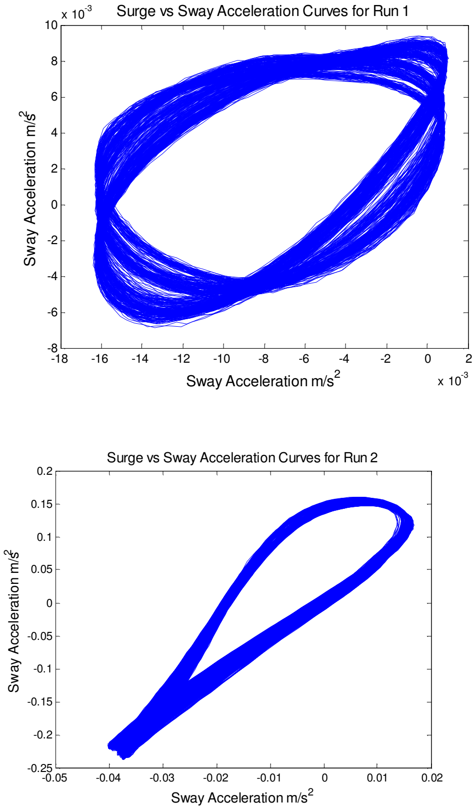

Figure 11: Surge Acceleration vs Sway Acceleration for λ/h = 50 & 25

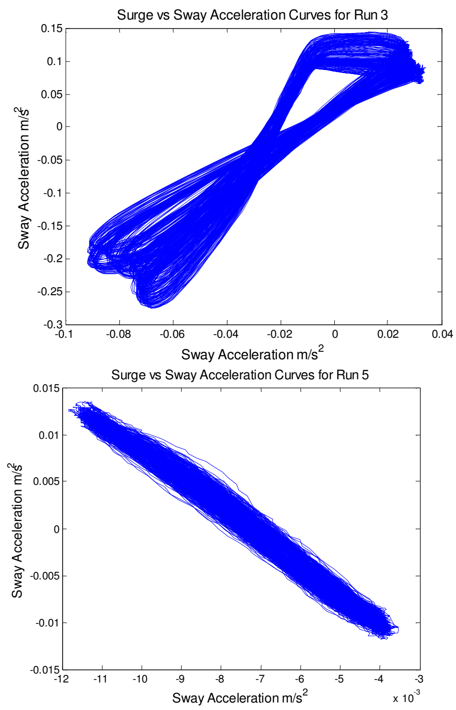

Figure 12: Surge Acceleration vs Sway Acceleration for λ/h = 15 & 93.3

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References

[1] ITTC, (2002) "Testing and Extrapolation Methods Loads and Responses, Sea Keeping Sea Keeping Experiments" ITTC – Recommended Procedures 7.5-02- 07-02.1.

[2] Paton, C G, Carra, C J and Sincock, P, (2006) "Investigation of Sway/Yaw Motions of Deepwater FPSOs", Proceedings Offshore Tech Conf, Paper OTC 18039, Houston.

[3] Brown, D T, and Liu, F, (1999) "Yawing of Turret Moored Vessels: Experimental Methods", Proceedings 9th Intl. Offshore Polar Eng. Conf. Brest, France.

[4] Young I.R. (2003) "A review of the sea state generated by hurricanes" Marine structures, vol. 16 pp. 201-218.

[5] CMPT 1998, Floating Structures: A guide for design and analysis Vol one, Oilfield Publications, England, UK

[6] Guedes Soares et. al 2005, "Experimental and Numerical Study of the Motions of a turret Moored FPSO in Waves", ASME J. Offshore Mech. Arct. Eng., 127, pp-197-204

[7] Martijn et. al., "On the sensitivity of the roll motion of an FPSO", Proceedings of OMAE Oslo 2002