16th Australasian Fluid Mechanics Conference
Crown Plaza, Gold Coast, Australia
2-7 December 2007

Parametric Study of Yaw Instability of a Weathervaning Platform

A. Yadav, S. Varghese and K. P. Thiagarajan[1]

School of Mechanical Engineering
University of Western Australia, Western Australia, 6009 AUSTRALIA

Abstract

Problems relating to weathervaning have been reported due to yaw instability in various Floating, Production, Storage and Offloading (FPSO) systems operating around the world thus disrupting the production/deck operations. Hydrodynamic analyses are economical means of analysing the dynamics of a turret based system when subjected to different sea states. The numerical results are verified by model tests to establish reliability of the results. A parametric study of the turret-moored FPSO is conducted using the AQWA suite of hydrodynamic software to evaluate the effect of the same in yaw instability. The parameters studied include Turret position and hull length. The numerical results are compared to model tests. The FPSO was observed to weathervane and reach equilibrium at an angle to the incident waves. This paper assesses the effect of these parameters and compares the same with the model test results.

Introduction

In the offshore oil and gas industry, FPSOs are becoming common production options as the industry progresses to deeper waters and in economization of marginal fields. This is greatly attributed to the short-lead time for conversion of existent ship hulls, ability to easily disconnect and to high storage capacities. A FPSO is normally a tanker hull held in position by mooring lines connected to a turret. This is a single point mooring system composed of a bearing connected to the ship hull and held by moorings to the seabed. The turret allows the FPSO to be aligned with the resultant of the environmental forces, thereby minimising motions and structural loads. The six degrees of freedom motions for a ship shaped hull are shown in Fig.1. The FPSO motion response, primarily roll, influences many operations onboard and are taken into consideration during the design of various topsides-equipment.

Yaw motion, being a horizontal plane motion is a low frequency motion with a typical natural period of 100 seconds for a ship shaped hull. Simos et al (1998) [1], describe the position of the mooring line attachment at the ship to be the control parameter governing yaw equilibrium. O'Donoghue and Linfoot (1991) [2], mention that the yaw spectra can have two peaks. The spectral content at higher frequency is lesser than at lower frequency but this explains the coupling with sway motion. Paton et al. 2005 [3] observed high sway yaw coupled motions and inefficiency of the mathematical tools to predict such motions.

During recent experiments described by Pistani and Thiagarajan (2007) [4] a FPSO model showed yaw instability in regular waves and bi-directional sea states. The FPSO did not weathervane into the sea but instead found equilibrium at an angle ranging from 10-50 degrees with the oncoming seas. This has the potential of increasing the magnitude of environmental loads on the hull, and defeats the purpose of installing a turret moored system. The project team has subsequently initiated a

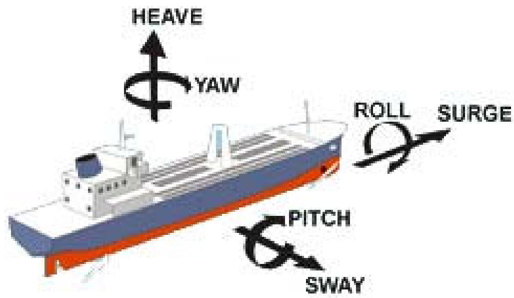

Figure 1. FPSO 6 DOF motions (www.km.kongsberg.com)

parametric study investigating the importance of various parameters affecting yaw motion. We present here some preliminary findings based on two important parameters – turret position and length of the hull.

Model Experiments

The model experiments were done at the Institute for Ocean Technology, Canada, in collaboration with the University of Western Australia. The Ocean Basin was 75 m long, 32 m wide and a water depth of 2.8 m. The tests were carried out on a 1:60 scale model of a generic FPSO based on dimensions of a VLCC operating at a lightship draft. The specifics of the model are given in Table 1.The FPSO model was moored in position by four instrumented mooring lines of stiffness 40N/m attached to an internal turret about which the model could weathervane. The turret was located at 20% length from the bow. The model angular velocities and transitional accelerations were measured using optical and inertial sensors. Four capacitance wave probes were located in between the wave makers and the model for recording the incoming wave conditions. 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 for calibrating the basin and for having measurements of the sea state without the model in place. Refer to Munipalli et al (2007) [5] for further details, including uncertainty estimates in experiments.

Numerical Model

The parametric study was conducted by utilising the boundary element software suite, AQWA [6]. The full scale numerical model was developed as shown in Fig. 2. Froude scaling laws were used to scale relevant values from the model test to full-scale values. AQWA-LINE, a frequency-domain 3-D diffraction and radiation analysis program was used to calculate linearised hydrodynamic wave loading on the FPSO. The radiation/ diffraction theory implemented for the analysis is usually used on bodies that cause scattering of the incident regular waves. The AQWA-LINE calculation provides first order and second order wave loadings on the FPSO. The fluid forces consist of reactive and active wave excitation forces. The reactive fluid loading such as added mass and wave damping is due to body motions that

[1] Corresponding Author: Ph +61 6488 7314 email: krisht@cyllene.uwa.edu.au

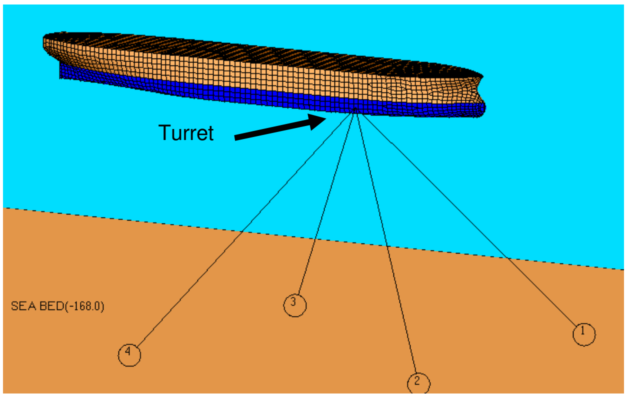

Figure 2: AQWA Numerical Model showing diffracted elements
.

cause the fluid to react on the body. The wave excitation loading is composed of diffraction forces due to scattering of the incident wave field and Froude-Krylov (FK) forces due to pressure field in the undisturbed incident wave.

The incident wave acting on the body is assumed to be harmonic and of small amplitude compared to its length. The fluid is assumed to be ideal and potential flow theory is used. The hydrostatic forces are combined with the hydrodynamic forces and FPSO mass characteristics to calculate the small amplitude rigid body response about at equilibrium mean position. The solution technique uses a distribution of fluid singularities over the mean wetted surface of the body. Since the motion is assumed to be harmonic, the solution is performed in the frequency domain. The harmonic response characteristics are referred to as Response Amplitude Operators (RAOs) and are presented as response amplitude per unit wave amplitude.

The second order wave drift forces which occur at frequencies lower than the wave frequency are important for the analysis of horizontal motions of floating bodies. AQWA-LINE uses the near-field solution where forces in all six degrees of freedom are calculated. The second order transfer functions are then calculated and can be used to express the second order wave forces in the frequency domain as force spectra or in the time domain as time histories. The accuracy of the program is well documented, and on par with other boundary element methods in existence.

AQWA-NAUT is a time-domain program used for analysis of wave frequency structure motion and mooring tensions. Non-linear hydrostatic and FK forces along with other forces are recalculated at each time step to give the resultant accelerations. The position and velocity are determined by integrating these accelerations in the time domain which on repetition with the following time-steps give the time history of the structure motion. The four mooring lines are modelled using linear elastic elements of stiffness 144kN/m.

Results & Analysis
Frequency domain analyses conducted on the model test results showed that the yaw response was non-linear in nature as yaw increased significantly with increase in wave steepness (Munipalli et al. (2005) [5]). To further understand this, time domain simulations were conducted in AQWA-NAUT for the test matrix listed in Table 2. All runs were conducted in regular wave with initial heading of zero degrees. As the regular waves are incident on the model, it was observed to drift in yaw, and ultimately reaching an equilibrium heading angle. Numerical model showed significant yaw instability during the regular wave runs similar to the model tests. Fig. 3 shows the equilibrium

Table 1: Model geometric particulars

Parameter	Value	
Length Over All (LOA)	329	meters
Length between perpendiculars (Lpp)	318	meters
Beam (b)	57.24	meters
Depth (d)	28.2	meters
Draft (D)	10.56	meters
Displacement (W)	145800	Tonnes
Turret Location (L_T); fore of aft perpendicular	263.6	meters
Longitudinal Centre of Gravity (LCG); fore of aft perpendicular	174.6	meters
Vertical Centre of Gravity (VCG); height above keel	17.04	meters
Transverse Centre of gravity (TCG); from center line	0	meters
Water plane Area (A_W)	14673.6	meters^2

Table 2: Model test matrix

Run No.	λ / LPP	λ / H	$T_{\text{Full Scale}}$ [s]	$H_{\text{Full Scale}}$ [m]
1	0.50000	50	10.091	3.180
2	0.66667	50	11.653	4.240
3	0.83333	50	13.028	5.300
4	1.00000	50	14.271	6.360
5	1.16667	50	15.415	7.420
6	1.33333	50	16.479	8.480
7	1.50000	50	17.479	9.540
8	1.66667	50	18.424	10.600
9	1.83333	50	19.324	11.660
10	2.00000	50	20.183	12.720

position obtained in simulations and the maximum heading from the model test runs. The simulations and experiments exhibit similar trends, although the experimental data is much higher. Higher yaw angles were generally observed over a range of wavelength to ship length ratio of 0.6 – 1.6.

It should be noted that the experimental model did not reach equilibrium for the short duration runs (Fig. 3) as the primary aim of these runs was to calculate linear transfer functions. It is expected that the final equilibrium angle would have been lower than that shown in Fig. 3 because of overshoot during transition. To understand this aspect, limited model test runs were conducted for a longer duration. Fig. 4 shows the model heading time history run for one such long duration run at wave amplitude of 3.71m and wave period of 15.41 secs. The heading changes rapidly to 42 degrees before reaching a minimum of 27 degrees and finally settling at equilibrium of 33 degrees with head sea.

Parametric study of yaw instability
To understand the dependence of yaw instability, a parametric study is being conducted using a numerical model. The study aims to verify the dependence of yaw on various hull and wave parameters. We present here preliminary results for the following two parameters:

1. Hull length
2. Turret Position

Mooring stiffness was initially considered a parameter of interest but the preliminary numerical model analysis concluded that yaw equilibrium is not influenced by increase in mooring stiffness.

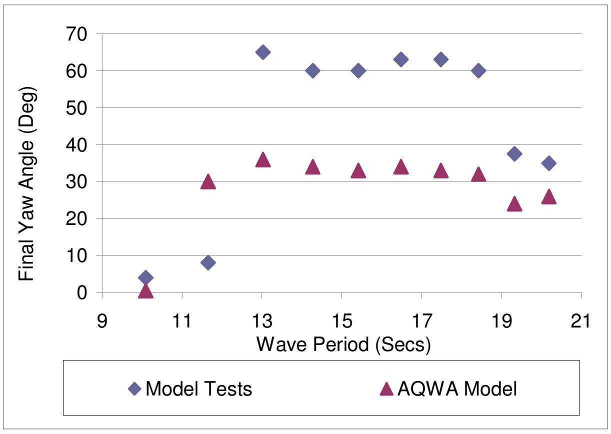

Figure 3: Comparison of AQWA model results and experiment model-test results

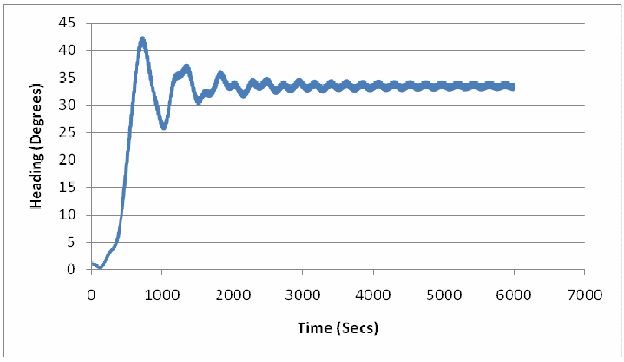

Figure 4: Time series plot for Wave period 15.41 secs; Amplitude: 3.71m; Wave Steepness: 1/50

Ship length

For the test runs, the model maintained the heading into the waves for the frequencies between 0.62 rad/sec to 0.48 rad/sec. But the yaw equilibrium increased significantly as the incident wave frequency was further decreased. It was identified that the sudden increase in yaw equilibrium angle might be attributed to either the frequency of incident wave (0.48 rad/sec) being very close to the natural roll period, or the wavelength to ship length ratio being close to 1. The length of numerical model was then changed without significant change in roll period, and further runs were conducted.

Three hulls with different lengths (Table 3) were run with the same draft and the turret position from aft perpendicular to ship length ratio was kept constant at 0.8. The results are shown in Fig 5. The standard test wave runs (Ref: Table 2) were done for all the three hulls with incident wave frequencies from 0.62 rad/sec to 0.31 rad/sec (wavelength to ship length ratio varying from 0.3 to 1.7). All three hulls were observed to head into the incident waves for the wavelength to ship length ratio less than 0.6 but as this ratio increased above 0.6, increase in yaw equilibrium angle was observed for all three hulls. Fig 5 shows the sudden increase in yaw by closely plotted contour plot lines between the wavelength to ship length ratio of 0.55 and 0.65. The hull no. 3 was observed to attain relatively higher yaw equilibrium angle than other two hulls which may attribute to high ship length to breadth ratio. Hence it was concluded that the yaw is more influence by ship length to wavelength ration than the natural period in roll.

Table 3 : Particulars for model and long hulls

Hull no.	Length	Beam	Depth
Model	318	57.24	28.2
Hull 2	396	57.24	28.2
Hull 3	490	57.24	28.2

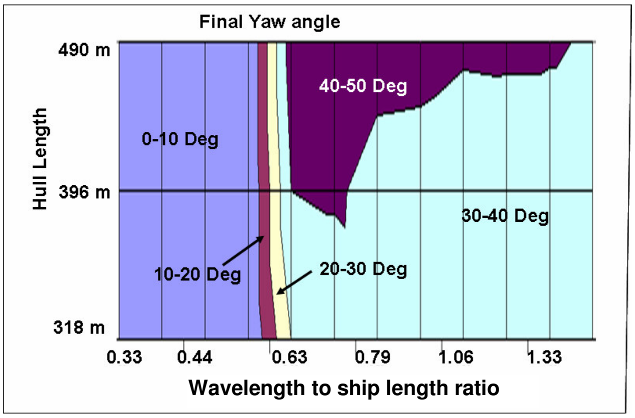

Figure 5: Influence of hull length on Yaw

Turret Position

Turret position is an important parameter influencing yaw stability. The horizontal and vertical forces are highly influenced by the position of the turret. The turret can be located anywhere from bow to midship and sometimes even near the stern. O'Donoghue and Linfoot (1991) [2] emphasize the importance of the position of turret. They further explain that the lever arm of hydrodynamic restoring forces due to wave action on the side of the ship increases with the distance between the turret and the LCG. The same was observed in the AQWA model and shown in Fig-6 (contour plot). Turret positions adopted for the AQWA runs are as tabulated in Table 4.

The vessel yaw equilibrium was observed to increase as the turret moves closer to midship. The sway force acting on the centre of gravity translates to be the moment arm acting on the turret to weathervane which increases as the turret is located forward. It was observed that as the turret moved closer to midship, the amplitude yaw about the equilibrium position increase significantly. Hence, the moments in yaw about the turret due to the portion of hull ahead of turret cannot be discarded for the internal turret cases as these moments may act as destabilising moments thus increasing the yaw equilibrium angle. The passive weathervaning capabilities of an FPSO with the turret close to the midship are very weak and are to be complimented by active weathervaning devices like bow and stern thrusters.

There were significant affects of turret position variation in horizontal plane motions of the vessel but no significant change in vertical plane motions of the vessel. The excursion of the hull was observed to increase as the turret moved closer to midships.

Table 4: Turret Position Variation

Turret Location; fore of aft Perpendicular	Value
100 % Lpp	318 meters
90% of Lpp	287 meters
80% of Lpp (Model turret position)	263 meters
70% of Lpp	222 Meters

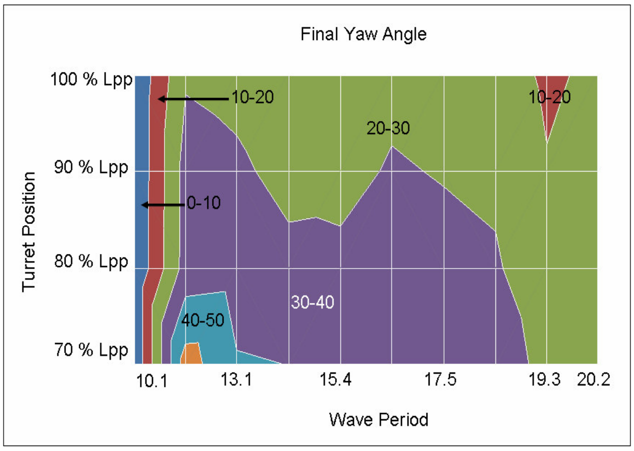

Figure 6: Dependence of yaw angle on turret position

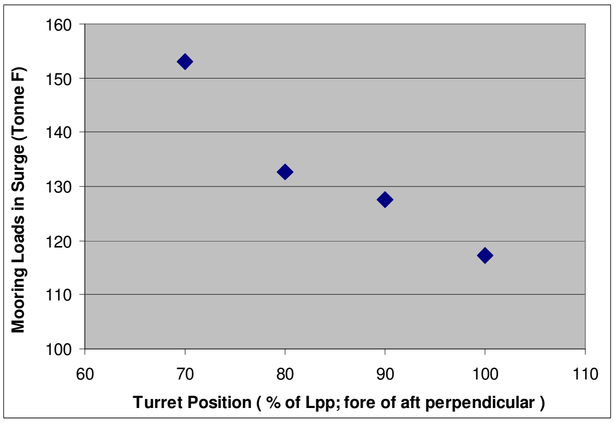

Figure 7: Average mooring load in surge

The excursion increase leads to increase in sway motion as the turret is positioned closer to midships. The surge motion is also observed to reduce as turret moves away from the centre of gravity. The reduction in motions is also observed as the mooring loads decreases as the turret is moved closer to bow. Fig-7 shows the variation of average mooring force acting in surge direction at the yaw equilibrium position with the turret position. The surge motions may partly attribute to the coupling effect of sway yaw motions resulting in higher yaw equilibrium angle.

There is no significant difference observed in heave and pitch motions of the vessel as the turret position is varied, however, the vertical motions at the turret are increased significantly as the turret position is varied towards bow thus inducing high vertical loads on turret. The internal turret vessel's roll was higher than the model with turret close to bow, primarily because of yaw equilibrium angle being higher in case of internal turret FPSO. However, the rate of change of roll with change of yaw remained constant for same wave at various turret positions.

It was also observed that when vessel's maximum yaw occurs, the stern transom is submerged. The high yaw instability, to some extent, may be attributed to the submergence of vessel's transom in the water as the incident wave amplitude increases. The submergence of vessel's transom reduces as the incident wave period increases. The sudden submergence of transom in the wave results in higher yaw equilibrium angles as suggested by preliminary numerical model analysis.

Conclusions

The paper aims at a parametric study of Yaw instability observed on Moored FPSO. Following are the finding of the Paper:

1. The FPSO shows a higher degree of instability in yaw with wavelength to the length of the ship ratio of 0.6 to 1.7 at large amplitudes. Yaw equilibrium angle is observed to significantly higher for an internal turret FPSO especially when wavelength is proximal to ship length.

2. FPSOs with bow turret are less susceptible to the yaw instabilities than internal turret FPSOs. The equilibrium yaw angle increases with the turret position drawn closer to mid-ship section.

Further parametric studies are currently underway examining the influence of:

1. Position of Centre of Gravity
2. Study of external turret vs internal turret
3. Hull Geometry
4. Slenderness of the hull

Acknowledgments

The authors acknowledge the support of ANSYS (via LEAP Australia) for providing AQWA software used in this study. The authors acknowledge the support of Jayanth Munipalli during this study. The experiments were conducted at the Institute of Ocean Technology, Canada, which was partially funded by the Australian Research Council.

References

[1] Simos A N, Tannuri E A, Pesce C P, 'Dynamics of a turret-FPSO system and hydrodynamic models', (1998) OMAE98-0410

[2] O'Donoghue T. And B.T. Linfoot., 'An Experimental Study of Turret Moored floating production systems', Applied Ocean Research 14 (1992) 127-139

[3] Paton C G, Carra C J, and Sincock P, Investigation of Sway Yaw motions of a Deep water FPSO, (2006) OTC 18039, Houston.

[4] Pistani, F and Thiagarajan, K P, (2007) "Experimental campaign on a moored FPSO in complex, bi-directional seastates", *Proceedings* Int. Conf. Water Waves Floating Bodies (IWWWFB), Plitvice, Croatia.

[5] Munipalli, J, Pistani F, Thiagarajan K P, Winsor F and Colbourne B, 'Weathervaning instabilities of a FPSO in Regular waves and consequences on Response Amplitude Operators', (2007) OMAE2007-29359

[6] AQWA User manual, Horsham (UK), Century Dynamics Ltd., RH12 2DT, 2004