Study of the Stability of Turret moored Floating Body

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ABSTRACT

Turret moored floating platforms, such as FPSO, FSRU and FSU weathervane on a turret to wave, current and wind. Turret is a single point mooring system and usual floating platforms has bilateral symmetry with respect to the longitudinal axis. So, these vessels can oscillate from side to side or move to one particular direction, and eventually shows large yaw motion. Yaw of these vessels is one of factors to affect the motion, mooring load and offloading operation. In the tandem and side-by-side configuration, yaw is more important which influences on STS (Ship To Ship) mooring, operation possibility (downtime). It is necessary that the behavior of yaw should be analyzed thoroughly for the design of mooring system and the assessment of operability and safety. In order to investigate the behavior of yaw, some analytic studies and experiments were carried out at MOERI’s ocean engineering basin.

To analyse the stability, the analytic method was used considering the static and dynamic stability. The equations of motion are linearized for stability analysis. The hydrodynamic forces were calculated by solving the boundary value problem which is solved by the higher-order boundary element method. To verify the analysis method, the results of a single floating body were compared with that of experiments. The turret moored vessel was unstable from regular wave period 15 to 20 sec, but stable in irregular waves. The results of model test show that the possibility of large yaw in irregular wave can be predicted by the regular wave tests. It is considered that this stability analysis could be applied to various side-by-side configuration and could give us the dynamic characteristics.

KEYWORDS

Turret; FPSO; Weathervane; Yaw; Stability

INTRODUCTION

Turret is a typical mooring system for offshore floating structure, such as FPSO, FSRU and LNG-RV. Turret is used for stationkeeping in harsh environments; heavy sea, high winds and strong current. The most important function of turret is weathervaning which allows vessel to rotate freely around turret. So yaw motion and stability are interesting feature and important design factor. Many research have been done up to now. Bernitsas and Papoulias (1986) conducted the study on the yaw and stability of single point mooring. Lee and Choi (2005) studied the stability of tandem configuration. Yaw of turret moored vessels in regular waves was investigated Liu et al (1999) and large yaw motion was explained by the balancing of drift forces and moments. O'Donoghue and Linfoot (1992) performed the model test in irregular waves and reported the effect of turret position and mooring load characteristics. Recently, Yadav et al. (2007) conducted the parametric study of large yaw motion in regular waves by doing time domain analysis. Munipalli and Thiagarajan (2007) showed the effect of wave steepness on the yaw motion and mention the relation of sway and yaw acceleration for large yaw motion case. Jiang et al. (1995) extensively reported the horizontal motions and mooring line loads of single point moored tanker. Cho (2012, 2013) studied the motion behavior and stability of turret moored floating body and two bodies including sloshing.

In this study, the model test and stability analysis have been done for a turret moored FSRU. Turret is connected to catenary mooring lines. Model tests are performed in regular waves. Trajectories of motion, velocity and acceleration and phase plots of yaw are for horizontal motions. Stability analysis is applied to linearized horizontal equation of motion. The results are compared with experiment results.

EXPERIMENT

Experiments were carried out at MOERI/KIOST's ocean engineering basin. The basin is 56 m long, 30 m wide and a water depth is 3.3 m. The tests were carried out on a 1:60 scale model. The water depth for the proto type is 192m. The floating structure used in experiments is FSRU (Floating Storage and Regasfication Unit) and main particulars are shown in Table 1. FSRU is moored by the internal turret and catenary mooring lines. Fig. 1 and 2 show FSRU model, turret and mooring line model. The mooring lines are made by chain and the similitude between proto and model is applied for weight in water and stiffness. Table 2 shows the properties of mooring lines. Turret is located at $0.45L_{BP}$ form CoG. The loadcells are installed to measure the force acting on the turret and the tension of mooring lines. The catenary mooring lines is arranged 3 by 3 and each line's pre-tension is 1,670 kN and the natural period of surge is 201 sec in proto type scale. Fig. 3 shows the layout of mooring lines which anchor point of line 1, 2 and 3 is 1,080 m from turret horizontally and anchor point of line 4~9 is 720 m. Fig. 4 shows the result of static pull-out test. In this study, incoming wave direction is only one case, head sea and then surge, sway and yaw motion are dominant. To confirm the restoring force of mooring lines, static pull-out test is conducted in surge direction.

Model tests were carried out in regular waves. The conditions of regular waves are summarized in Table 3. The wave steepness of regular wave is fixed as 1/50 and 1/30.

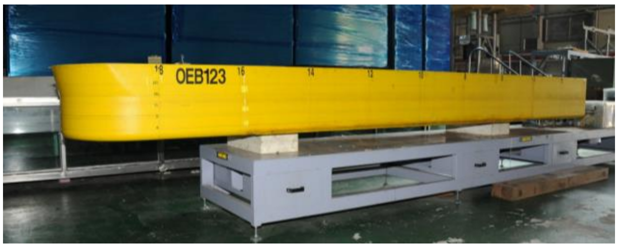

Fig. 1: FSRU model

Fig. 2: Turret mode and chain for mooring line

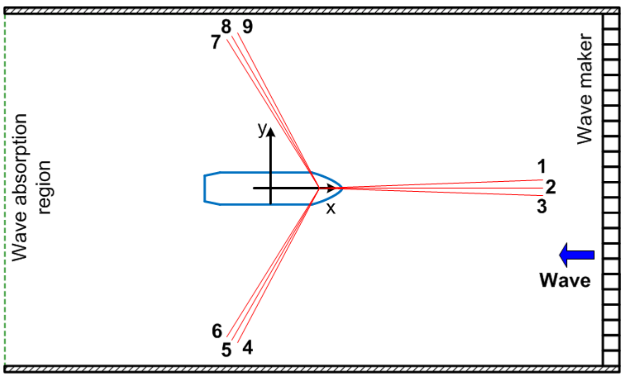

Fig. 3: Layout of mooring lines

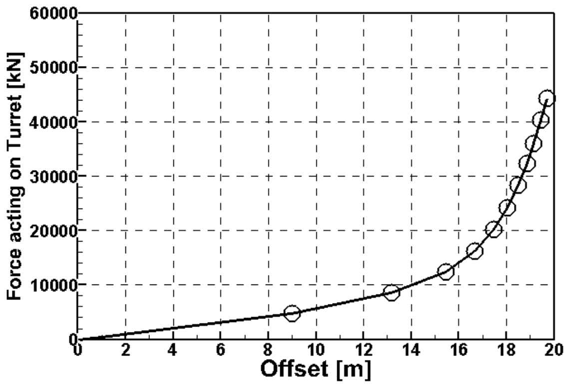

Fig. 4: Restoring curve of a turret moored FSRU

Table 1: Main particulars of model

Particulars	Abbr.	
Length	L_{BP}	315 m
Breadth	B	53 m
Draft	T	12 m
Disp.	∇	200,331 ton

Table 2: Properties of mooring line

Items	
Weight in water	4,0002.7 N/m
Stiffness	2,351,880 kgf/m

Table 3: Conditions of regular waves

T [sec]	λ [m]	λ/L_{BP}
6.0	56.18	0.18
8.0	99.88	0.32
10.0	156.07	0.50
12.0	222.27	0.71
13.0	257.86	0.84
14.0	294.11	0.97
15.0	330.52	1.11
16.0	366.76	1.27
17.0	402.67	1.43
18.0	438.19	1.61
19.0	473.28	1.79
20.0	507.97	1.98
22.0	576.24	2.40

STABILITY ANALYSIS

To investigate the motion characteristics of turret moored FSRU in waves, static and dynamic stabilities are analyzed by using simplified equation of motion. Only horizontal planar motions (surge, sway and yaw) are considered here.

Two coordinates are used. The o-xy is the body fixed coordinate system with origin located at the turret center. The O-XY is the inertial coordinate system fixed to the earth. Analysis is done on assumptions that 1) the mean velocity of body is zero, 2) motion is very slow, 3) there are no wind and current and 4) the relative motion is not considered. The hydrodynamic forces and wave drift forces are calculated on o-xy coordinate. Fig. 5 shows the coordinate systems of turret moored floating body.

There is a procedure of stability analysis. First, find the equilibrium points of equations of motion. Second, linearize the equations of motion near these equilibrium points by means of a Taylor expansion. Third, analyze the static stability. Finally find the dynamic stability. The equilibrium point of equations of motion is assumed as a stationary state of floating body having zero yaw angle (that is, head sea condition, 180 deg). Nonlinear equations of motion are linearized near this equilibrium point. Then the linearized equations for surge, sway and yaw are derived as follows.

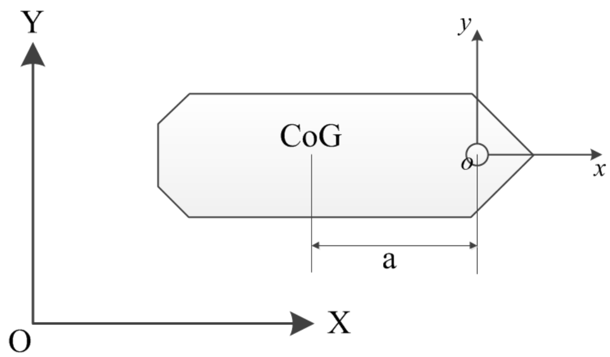

Fig. 5: Coordinate system of floating body

$$M\ddot{x} + Sx = 0 \tag{1}$$

$$M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{26} \\ 0 & m_{62} & m_{66} \end{bmatrix} \tag{2}$$

$$S = \begin{bmatrix} K & 0 & 0 \\ 0 & K & aK - \dfrac{dY}{d\psi} \\ 0 & aK & a^2K - \dfrac{dN}{d\psi} \end{bmatrix} \tag{3}$$

where M is mass matrix that include added mass and S is the restoring stiffness matrix, K is the turret mooring stiffness matrix, time mean sway drift force (Y), time mean yaw moment (N), a is distance from CoG to turret and ψ is heading angle of FSRU respectively.

The condition of static stability is that the restoring moment of the equations is positive at static equilibrium point. It means that the determinant of stiffness matrix S should be positive.

$$\det[S] = K^2\left(a\frac{dY}{d\psi} - \frac{dN}{d\psi}\right) > 0 \tag{4}$$

To satisfy the above inequality, the value in parenthesis must be positive. The moment induced by the sway drift force must be larger than the yaw moment. And the critical turret position, a_{cr} is expressed by Eq. 5.

$$a_{cr} = \frac{dN/d\psi}{dY/d\psi} \tag{5}$$

The dynamic stability can be determined by checking the eigenvalues. We can write the motion vectors as follows.

$$x(t) = Xe^{\sigma t} \tag{6}$$

The sign of eigenvalue provide us the information on the characteristics of dynamic stability. Fig. 6 shows the graphical representation of stability. If eigenvalue have a positive real part, the system will be unstable and divergent with time. When eigenvalue is zero, the system will remain as initial state or oscillate with constant amplitude. If eigenvalue have a negative real part, the system will be stable.

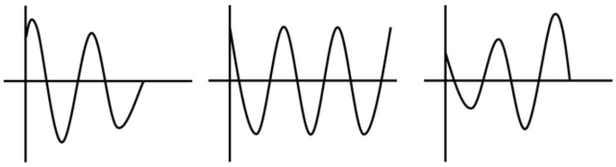

Fig. 6: Graphical representation of stability

Eigenvalue can be calculated by substituting Eq. 6 to 1 and we have Eq. 7.

$$(\sigma^2 M + S)Xe^{\sigma t} = 0 \tag{7}$$

To satisfy Eq. 7 for any X , the matrix of parenthesis must be singular. That is, the determinant of parenthesis must be zero. Eigenvalues can be obtained from Eq. 8.

$$p(\sigma) = \det[\sigma^2 M + S] = 0 \tag{8}$$

RESULTS

Analysis of Experimental Data

Time series of motions of FSRU are shown for wave period 12, 16 and 22 sec in Fig. 7. It is noted that the steady state is hardly obtained for turret moored FSRU in regular waves because FSRU moves continuously on a turret. Generally regular wave tests are carried on for a short time not including the reflection waves (ITTC, 2002). But long time analysis is needed for transient, long period motion and nonlinear behavior. In this study, data are recorded for a long time corresponding to 38 minutes in real time.

When wave period is 12 sec, FSRU slightly moves in longitudinal direction (surge) due to wave drift force, yaw increase slowly to 10 deg and then go to 6 deg finally. In the case of wave period 16 sec, FSRU do not move in longitudinal direction. Yaw increase continuously to 60 deg and converge to 50 deg. For wave period 22 sec, surge motion is due to large wave height and long wave and yaw go to 20 deg continuously. Fig. 9 shows the maximum yaw angle for wave periods. From 6 to 14 sec, the maximum yaw angles are bounded within 20 deg. From 15 to 22 sec, very large yaw occur 50 ~ 60 deg. This zone can be expressed in term of ratio of length of wave and FSRU and λ/L_{BP} is from 1.11 to 1.98. Yadav and Thiagarajan (2007) showed that large yaw occurred in the zone of λ/L_{BP} from 0.67 to 1.7. It is noted that large yaw motion is very slow. This indicates that large yaw is not wave induced motion which have the wave period, but the characteristics of FSRU, turret system and mooring system. In this study, the wave steepness does not influence the large yaw motion. Results show that yaw is reduced due to current acting as stabilizing force.

In theory, this problem has symmetry condition because of the symmetry of FSRU's geometry. The symmetry condition cannot be completely realized in model test. To confirm the repeatability and symmetry, model tests were repeated for same conditions. Fig. 10 shows the results of repeated tests. For wave slope 30, the very small initial offset is set to opposite direction from first results and the repeated tests show that yaw have the opposite sign confirming the symmetry. For wave period 16 sec, repeated test results for wave slope 30 and 50 indicate the results have good repeatability also.

Yaw in irregular waves are shown in Fig. 8. The results show that yaw is in ±5 deg. Better yaw restoring moment acts in all irregular waves than regular waves. The peak wave periods are marked in Fig. 9 showing all periods in the stable Zone I. To confirm the relation between regular wave results and irregular wave results, FPSO model having different condition was tested and the results are shown in Fig. 11 and 12. When the peak wave period is 9.5 sec in stable Zone I, yaw is bounded within 3 deg. On the other hand, when the peak wave period is 15.1 sec in unstable Zone II, yaw is very large, almost 30 deg in irregular wave. This shows that the possibility of large yaw in irregular waves can be predicted by the regular wave tests. It is noted that the regular wave tests are important to know the behaviour of yaw motion of turret moored vessels.

Stability Analysis

Static equilibrium point can be calculated by finding the balance of the moment exerted by sway drift force (Y) and yaw drift moment (N). Yaw satisfying Eq. 9, zero total moment is static equilibrium point. Total moment for ω=0.4rad/s is shown in Fig. 15. Drift force and moment are calculated by Higher-Order Boundary Element Method (Choi et al., 2001).

$$M_{NET} = aY(\psi) - N(\psi) \tag{9}$$

Fig. 13 shows the static equilibrium conditions. The dashed line represents the static equilibrium values satisfying Eq. 9. 180 deg is static equilibrium angle for all wave frequency. Another static equilibrium exists at wave frequency 0.35 rad/s and 0.47 rad/s. These wave frequencies coincide with occurrence frequency of large yaw motion.

Static stability is expressed Eq. 4 and shown in Fig. 14. The grey shaded region is unstable and white part is stable. The unstable region also coincide with the static equilibrium results between wave frequency 0.35 rad/s and 0.47 rad/s. This agrees with the results of model test. That is, the zone which large yaw motion occurs is an unstable region and vice versa, the unstable region is the zone which large yaw may occur.

CONCLUSIONS

In this study, yaw motion and stability of turret moored FSRU are studied in regular waves. Model tests are performed and horizontal motions are analyzed. Results show that large yaw motion occurs for particular wave period from 15 to 22 sec (λ/L_{BP} from 1.11 to 1.98). Maximum yaw angle is about 50 ~ 60 deg for this wave period. Also wave steepness does not affect the yaw motion. Large yaw motion in irregular waves may be predicted by the results of regular wave tests. Stability analysis shows good agreement with experiment. That is, yaw motions is explained by the balance of the moment exerted by sway drift force and yaw drift moment.

In order to understanding the behavior of turret moored vessel more, further study needs in current and wind. The behaviour of side-by-side moored two bodies will be investigated by using the same procedures. Also turret loads and mooring line tensions must be investigated together.

ACKNOWLEDMENTS

This study has been carried out as a part of project titled “Development of Engineering Technologies for Floating Offshore LNG Terminal” and “Development of Turret System for FPSO Operating at Hs 15m Seas” supported by Ministry of Knowledge Economy of KOREA and project titled “Performance Evaluation Technologies of Offshore Operability for Transport and Installation of Offshore Structures” supported by MOERI/KIOST.

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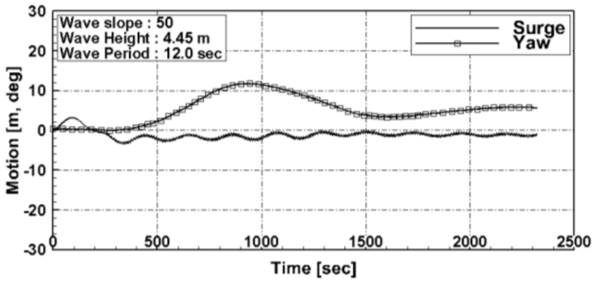
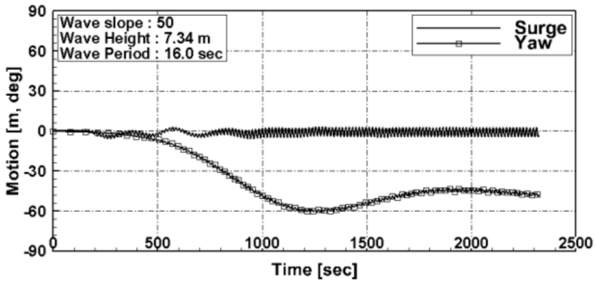
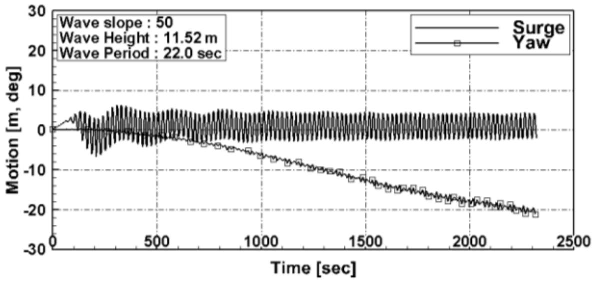


(a) Wave period 12 sec

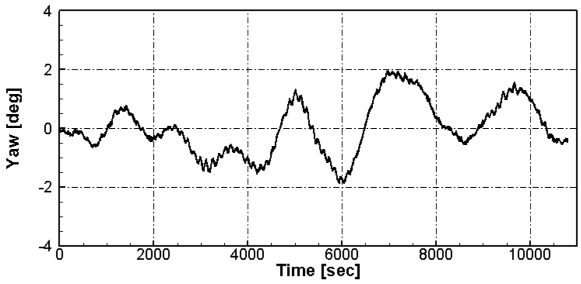


(b) Wave period 16 sec

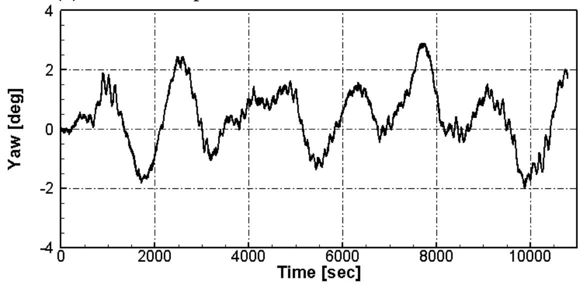


(c) Wave period 22 sec

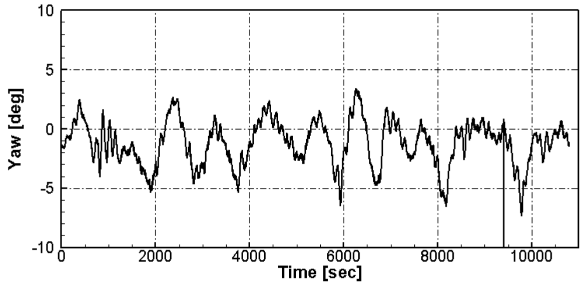
Fig. 7: Time series of motions of FSRU in regular waves (Wave steepness 50)



(a) Hs=3m, Tp=11sec



(b) Hs=5m, Tp=12.7sec



(c) Hs=11.9m, Tp=14.2sec

Fig. 8: Time series of yaw of FSRU in irregular wave

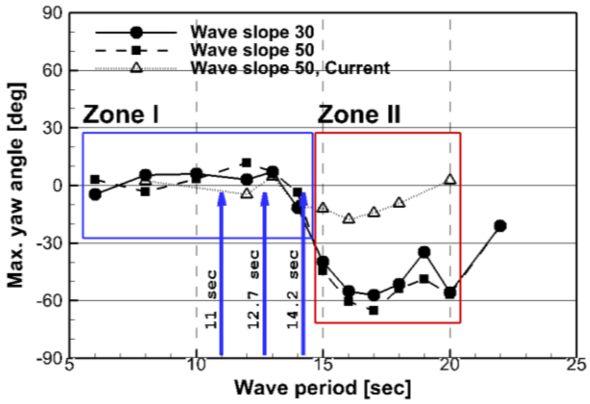


Fig. 9: Maximum yaw angle of turret moored FSRU for regular waves

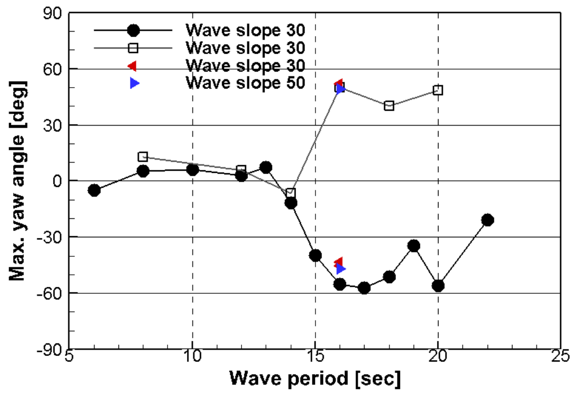
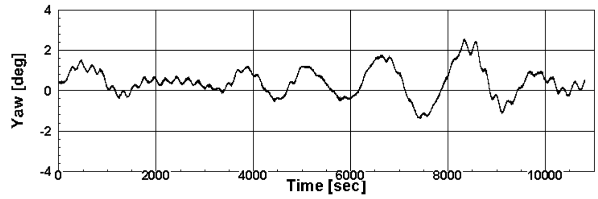
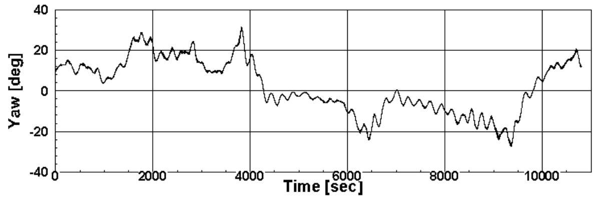


Fig. 10: Repetition test of turret moored FSRU for regular waves



(a) Hs=4 m, Tp=9.5 sec



(b) Hs=13.1 m, Tp=15.1 sec

Fig. 11: Yaw of FPSO in irregular wave

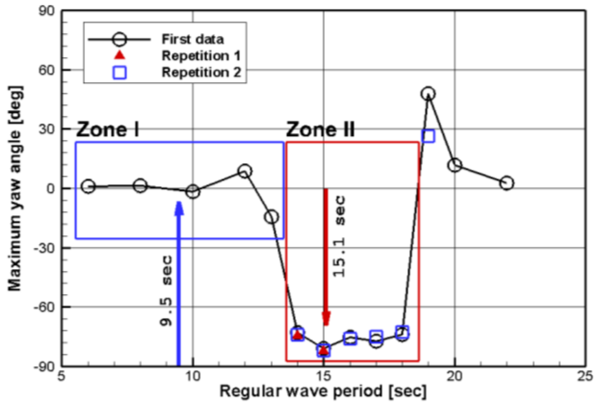


Fig. 12: Maximum yaw angle of turret moored FPSO for regular waves

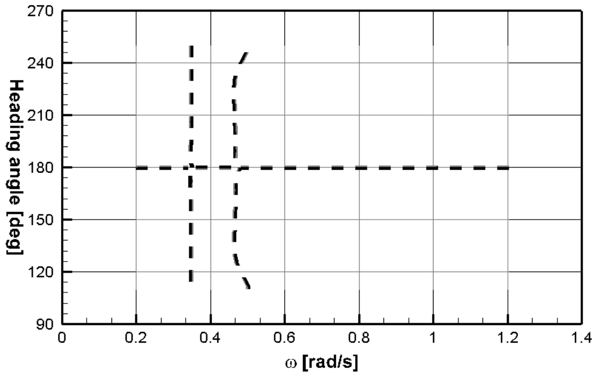


Fig. 13: Static equilibrium lines of FSRU

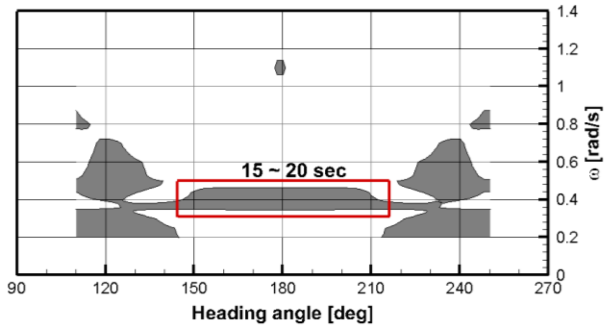


Fig. 14: Static stability plot of FSRU