Experimental Study on the Large Roll Motion of a ROPAX Ship in the Following and Quartering Waves

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ABSTRACT

The roll motion characteristics of a ROPAX ship is investigated by free running model tests in the ocean engineering tank of MOERI. All the tests are carried out in the regular waves. To find out the effects of wave conditions on roll motion, wave conditions have been varied with wave length, wave steepness, incident angle and model speed. The influence of GM is also investigated with two different weight conditions. Six degree of motion is measured using RODYM and Vertical gyro. The side hull wave profile is recorded by video camera which is synchronized with motion data. Since the model speed can not be increased up to critical speed due to the limit of the length of tank, the capsizing is not observed. However, large roll motions over 35 degrees were observed for several conditions. In most cases roll starts to develop largely when wave crest passes between A.P and 1/4L aft and the roll motion reaches maximum when the crest passes mid-ship. The maximum roll always occurs in the lee side and then the heading is to the weather side.

KEYWORDS

Large Roll Motion, Broaching-to, Free Running Test., performance-based criteria

INTRODUCTION

When a ship sailing in following or stern quartering seas encounters the waves with a longer period than in beam, head or bow waves, she could meet dangerous situations associated with surf-riding, broaching-to and pure loss of stability(IMO, 2006). However, the current IMO weather criterion is based on a beam wind and beam waves scenario so that it cannot consider such dangerous phenomena occurring in following and quartering seas. Furthermore, since weather criterion was developed and validated intrinsically based on old ship and empirical formulation, it is questionable to apply weather criterion for a modern ship which has different design from conventional ships(IMO, 2002).

With this background, IMO has started to work for developing performance based stability criteria to overcome the limit of current IMO weather criterion(IMO, 2003). In developing performance based stability criteria, numerical simulation and/or analytical methods for predicting large motions of a ship in waves are essential and they need to be validated by model tests for reliability. These methods are also required to review and improve the Guidance to the Masters for Avoiding Dangerous Situations in Following and Quartering Seas(MSC/Circ.707)(IMO,2006).

ITTC specialist committee on stability in waves have carried out benchmark tests to establish capability and weakness of existing numerical codes that have been developed for predicting extreme ship motions and capsizing of intact ships in waves(ITTC, 2002, 2005). On the motions in quartering seas, most numerical codes predicted capsizing observed in experiments, but there were large discrepancies in behaviour of motion overall. As reasons for discrepancies, the committee noted inaccuracy of force coefficients, coupling of manoeuvring model to seakeeping model, rudder-roll coupling and unknown initial conditions and position relative to the waves. The necessity of more structured and reliable experimental data for validation of numerical codes are also remarked.

This study has been done to develop numerical and experimental method to assess the stability of a ship in following and quartering sea directly with performance based stability criteria in mind. To understand the complicated phenomena occurring in following and quartering waves and have a benchmark data for numerical prediction, model test has been done. Tests have been made with a 2.5m free running model in the ocean engineering tank of MOERI. All the tests are carried out in the regular waves. To find out the effects of wave conditions on roll motion, wave conditions have been varied with wave length, wave steepness, incident angle and model speed. The influence of GM is also investigated with two different weight conditions.

TEST SHIP

The principal dimension of test ship, ROPAX is summarized in Table 1. Scale ratio of model ship is 1/70 and model ship is shown in Fig. 1.

Table 1: Principal Geometric Characteristics of ROPAX

Item	Ship	Model
Loa(m)	175.0	2.500
Lbp(m)	162.1	2.316
Breadth(m)	27.6	0.394
Draft(m)	6.976	0.100
GM#1(m)	2.47	0.0353
GM#1(m)	1.17	0.0167
Roll period#1(s)	13.8	1.7
Roll period#2(s)	21.8	2.6

Model ship equips with a watertight cover to protect gyro sensor and motor controller from water.(Choi 1999)

Fig. 1 Model ship of ROPAX

ASSESMENT OF WEATHER CRITERION

To see basic stability of the test ship, IMO Weather criterion was assessed by using the model test data which were obtained through the procedure suggested in the interim guidelines (Italy, 2004-2005), and the empirical formula enclosed in Code on Intact Stability (IMO, 2002). Tests for assessment of weather criterion consist of wind tunnel, drifting, and motion test in waves. Drifting and motion test in waves were performed in MOERI ocean engineering basin in 2006. Detailed procedure and results are presented in STAB2006 (Yoon et al, 2006).

Table 2 shows the results. Here, θ_0 and θ_1 denote heel angle and roll-back angle due to wave action, respectively. a and b are areas under the GZ curve, which are defined in detail in Code on Intact Stability(IMO, 2002). To satisfy Weather criterion, b must be greater than a . It can be seen that ROPAX satisfy weather criterion for loading condition GM#1 but does not satisfy for loading condition GM#1

Table 2: Assessment results of Weather criterion

Loading	GM#1		GM#2
Method	Formula	Test	Formula
θ_0 (°)	4.90	3.00	10.67
θ_1 (°)	-20.47	-18.09	-17.26
a (rad-m)	0.1996	0.1260	0.0842
b (rad-m)	0.3379	0.4845	0.0466
Assessment	Satisfy	Satisfy	Not satisfy

Fig. 2: Computerized Planar Motion Carriage(CPMC) of MOERI.

MODEL TEST

Test Facility and Measuring System

Tests were carried out in the ocean engineering tank(50m*35m) with Computerized Planar Motion Carriage (CPMC) in MOERI as shown in Fig.1. Six degree of motions are measured using RODYM together with a gyro. Rudder and propeller are controlled with two servomotors. AC power is supplied to all equipments on model ship through wire connected with CPMC. PC(Pentium-IV) onboard is used to control model ship and to store measured data with analog-to-digital converter. Fig.3 shows schematic diagram of free running system.

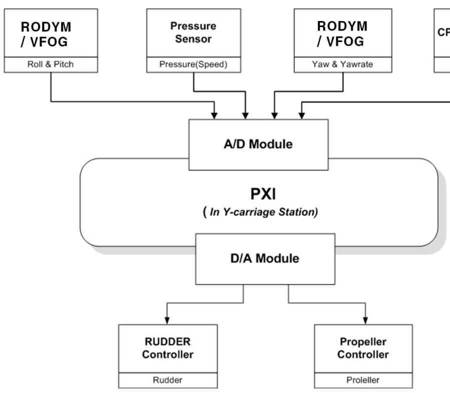

Fig. 3: Schematic Diagram of Free Running System

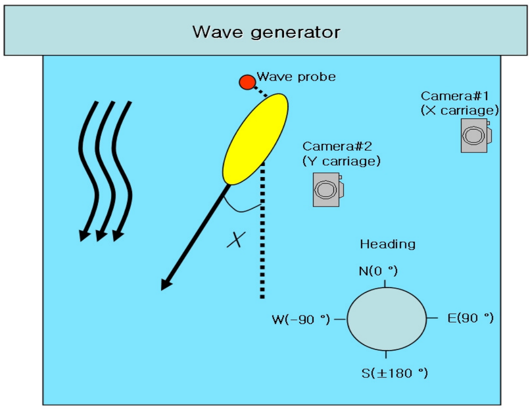

Fig. 4: Test Configuration

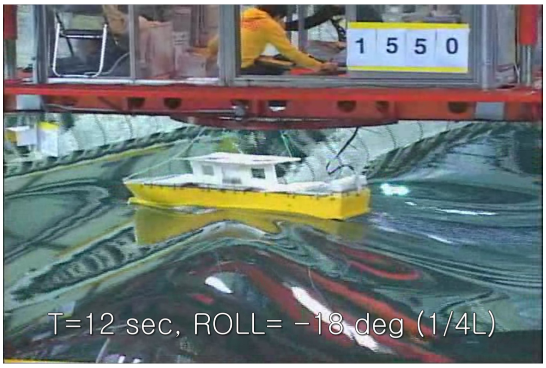

Fig. 5: A Snapshot of Wave Profile from Video Camera

Fig. 4 shows configuration of tests and coordinate system. Wave probe is installed just behind the model. Side hull wave profile is also measured with two video cameras. The video recording time is synchronized with other motion data to be compared. Fig. 5 shows a snapshot of side hull wave profile.

Test Conditions

All the tests are carried out in regular waves. Wave conditions are varied with wave length, wave steepness and wave direction. Wave conditions for tests are summarized in Table 3. Test speeds are 10 knots, 20 knots and 25knots. Due to the limit of length of tank, the speed can not be increased further so tested maximum Froude number is 0.33 which is much smaller than surf-riding condition. Wave directions are changed with 0, 15, 30 and 45 degrees.

Table 3: Wave Condition

No	λ/L	λ(m)	T(s)	H/ λ	H(m)
1	0.75	1.737	1.054	1/18	0.096
2	0.75	1.737	1.054	1/12	0.145
3	1	2.316	1.218	1/18	0.129
4	1	2.316	1.218	1/12	0.193
5	1.25	2.895	1.361	1/18	0.161
6	1.25	2.895	1.361	1/12	0.241
7	1.5	3.474	1.491	1/18	0.193
8	1.5	3.474	1.491	1/12	0.289

Since large roll motion does not occur with designed GM condition, 2.47m, (GM#1), tests are done also for lower GM condition, 1.2m, (GM#2). The total number of tests is 64.

EXPERIMENTAL RESULTS

Conditions of Large Roll Motion

There were some cases which show extreme roll motions up to 50 degrees. But there was no case which develops to capsizing. Fig. 6 shows one example large roll motion during test.

Here, the relations between large roll motion and conditions are investigated. The large roll motion is defined in this paper as the roll motion exceeding 35 degrees, just for convenience and without any rational basis. Table 4 shows the maximum roll angle for each test. At the condition of wave length to ship length ratio of 0.75 and 1.25, large roll motions are not observed.

Fig. 6: Photograph of Large Roll Motion in Quartering Sea (GM=1.2m, λ =1.5Lpp, Vs=25kts. χ=15deg, H/λ=1/18)

Table 4: Results of Maximum Roll Angle (deg)

GM (m)	Vs (kts)	Fn	λ (L)	H/λ	Encounter angle. χ(deg) (Scenario No) 0	15	30	45
2.47	10	0.13	1	1/18	9	15	10	5
				1/12	10	12	9	15
	20	0.26		1/18	-	-	6	-
				1/12	-	-	10	-
	25	0.33		1/18	10	12	8	13
				1/12	14	13	9	10
			1.5	1/18	-	12	6	12
				1/12	-	7	20	24
1.2	20	0.26	1	1/18	30	20	20	48
				1/12	39	24	18	-
	25	0.33		1/18	28	25	32	7
				1/12	17	25	10	18
			1.5	1/18	-	38	25	28
				1/12	-	43	14	55

With designed GM(=2.17m), most of maximum roll angle is lower than 20 degrees. The largest maximum angle is 24 degrees in case that wave length is 1.5L,d wave steepness is 1/12 and encounter angle is 45 degrees.

With smaller GM(=1.2m), large roll motions are observed on 5 test conditions shaded in Table 4. However, the correlation and the occurrence of large roll are not clearly seen. This is somewhat related with the short travel distance for present tests inevitable due to the limit of tank size. In general, large roll motions or capsizing in following and quartering waves need to time to develop and require a number of successive waves. However, in the present experiments, the running distance is so short that there may be many cases in which roll do not develop fully.

On the other hand, it is worthwhile to mention that all the large roll motions occur to the lee-side as same with previous capsizing test results(Kan 1990, Kan 1994).

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Developing Process of Large Roll Motion : quartering waves

To understand the mechanism of developing large roll motion, measured motion data are investigated further with measured side hull wave profile.

Fig. 7 shows time history of test No. 155 whose conditions are GM=1.2m, λ =1.5Lpp, Vs=25kts. χ=15deg, H/λ=1/18. Here, several dotted vertical lines mean the time point, when wave crest passes by ship. For example, there are time points of AP, 1/4 L from AP, Mid-ship, 3/4 L from AP. This point was obtained by analyzing video record of side hull wave profile.

Fig. 7 shows that a large roll motion occurs to the lee-side in 13 seconds, when heading angle is turned about 15 deg to the weather side from initial heading. Wave crest passes by the mid-ship when large roll motion occurs. Seeing the data from the beginning, for first two cycles of waves(see from t=5, and t=8), roll starts to increase to weather side direction as wave crest passes A.P. until wave crest passes 1/4L and after then roll decreases. However, for last cycle, roll does not increase to weather side direction and rather increase to lee side direction when wave crest passes from A.P. to 1/4L. After wave crest passes 1/4L, roll increases to lee side direction and reaches maximum angle until wave crest passes midship. The direction of roll motion is indicated in Fig. 8 with other motions. This is same with Grochowalski's experiments.(Grochowalski, 1989).

The main difference between the first two cycles and last cycle are direction of yaw rate. In the first two cycles, when wave crest passes between A.P. and 1/4L, yaw rate is negative or small in positive. So, the centrifugal forces act as a moment to weather side direction. But in the last cycle, yaw rate is positive and centrifugal forces act as a moment to lee side direction. When large wave crest passes midship, the restoring moments are negative for all roll angles as shown in Fig. 6. So, in this position, any small external force can increase roll angle greatly.

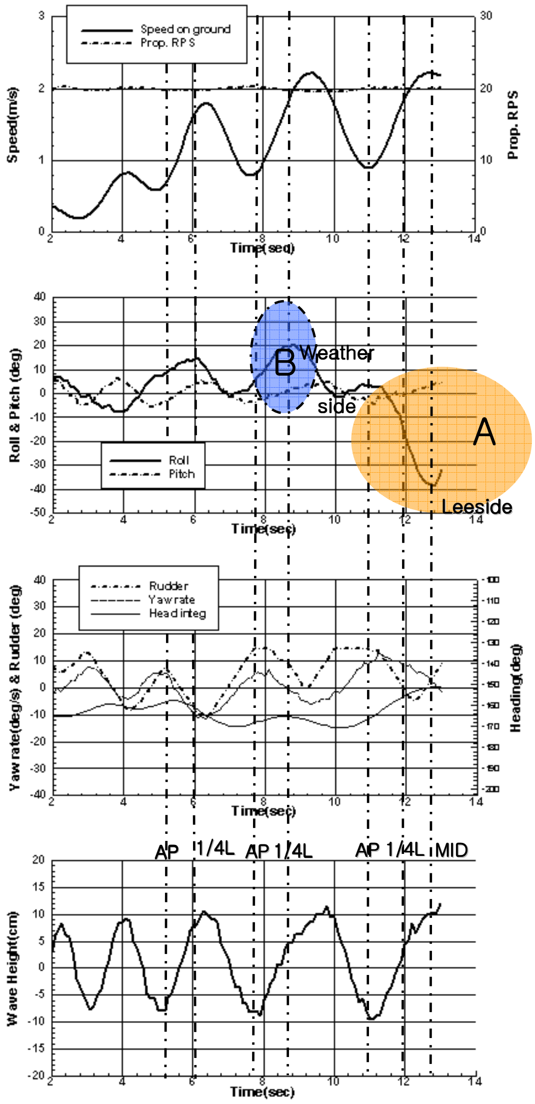

Fig. 7: Time history of Test No. 155 in Quartering Sea (GM=1.2m, λ =1.5Lpp, Vs=25kts. χ=15deg, H/λ=1/18)

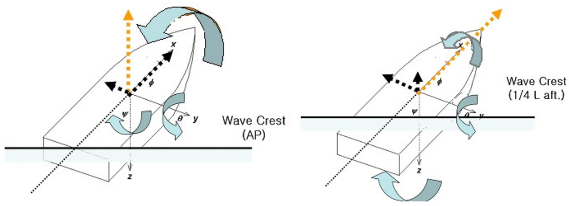

Fig. 8: Ship motion components in a quartering wave

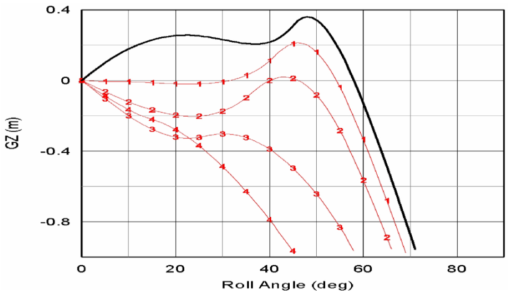

Fig. 9: GZ curves when wave crest passing by mid-ship (wave steepness: ①1/72, ②1/36, ③1/18, ④1/12)

For all cases, the developing process of large roll motion is similar with test No. 155. Grochowalski's experiments show also similar process to present data for last cycle. But Grochowalski's experiments show different roll characteristics for first two cycle. That is, peaks of roll angles are to the leeside direction for first two cycles. It is not clear at present for the reason of differences.

Developing Process of Large Roll Motion : following waves

Fig. 10 shows time history of test No. 152 whose conditions are GM=1.2m, λ =1.0Lpp, Vs=20kts. χ=0deg, H/λ=1/12. In this condition large roll motion occurs at 17 seconds. The measured maximum roll angle is 39degrees. Initial heading is the condition of following sea and heading is turned to the port side a little at the time of large roll motion. We can also see that final large roll occurs when wave crest passes mid-ship and direction is to the lee-side.

Similarly to test of No. 155, roll increases while wave crest is passing between AP and 1/4 L.

CONCLUSIONS

To understand the mechanism of large roll motions in following and quartering waves and to have a benchmark data for numerical simulation, free running model tests of ROPAX ship are carried out. Due to the limit of speed and tank size, capsizing does not occur but large roll angle over 40 degrees are observed for several conditions.

Using the measured motion data and side hull wave profile, developing process of large motion is investigated. Most of tests show that roll starts to develop largely when wave crest passes between A.P and 1/4L aft and the roll motion reaches maximum when the crest passes mid-ship. The maximum rolls always occur to the lee side and then the heading is to the weather side. It is found that in this process, yaw rate plays an important role to increase roll angles.

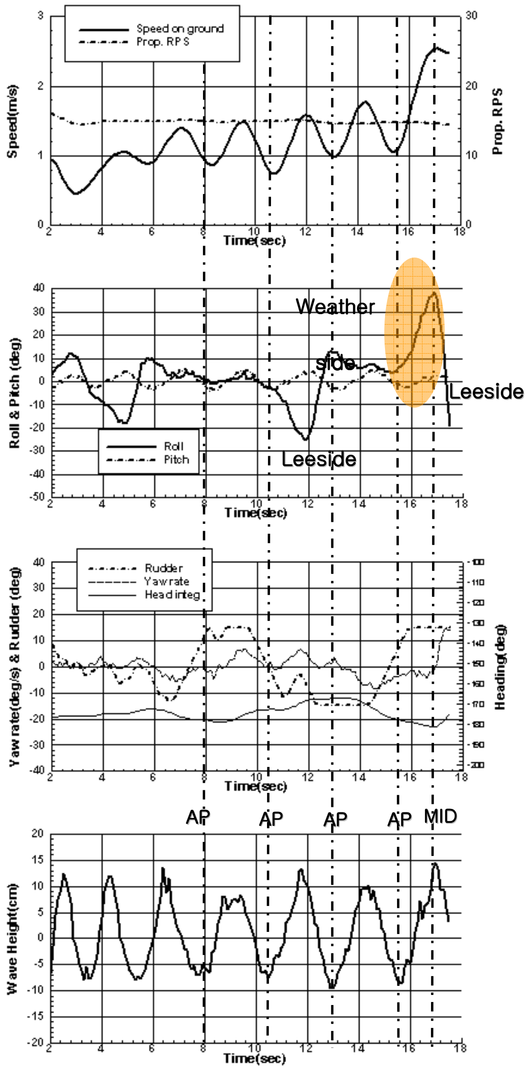

Fig. 10: Time history of Test No. 152 in following Sea (GM=1.2m, λ =1.0Lpp, Vs=20kts. χ=0deg, H/λ=1/12)

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