

Seaworthiness of Resonance-Free SWATH as an oceangoing fast ship

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ABSTRACT: The speed reduction, additional resistance or slamming, which are caused by the large amplitude of ship motions, should be restricted completely for oceangoing large fast ship, because of the strict time-punctuality and high value of the cargo. A “Resonance-Free SWATH (RFS)” as the oceangoing large fast ship has the negative restoring moments, which leads to resonance-free in the motion responses, because of the extraordinary small water plane area. The RFS is designed to cross 4,800 nautical miles of Pacific Ocean in 5 days punctually at a high speed of 40 knots, with the good seaworthiness such as no speed reduction or absolutely no slamming even in the rough sea. To verify the seaworthiness of the RFS, experiments in model basin and theoretical predictions are carried out to examine the lowest limit of motion responses in waves. The results in regular head waves are compared with those of various hull forms, such as mono-hull, ordinary SWATH or trimaran. The predominance of the RFS regarding seaworthiness will be pointed out in the conclusion. For example, by using PD control action, heave motion responses of the RFS is reduced to about 1/40 compared with those of mono-hull or trimaran, and pitch motion responses of the RFS become about 1/8.

1 INTRODUCTION

The developments of fast ships in various hull forms such as mono-hull, catamaran and trimaran are very active worldwide nowadays. Above all, the research and development of the oceangoing large fast ship is an important subject.

It is supposed that the perfect accuracy of navigation time schedule and delicate handling are required for the fast ships to transport the high-valued cargo even in the rough sea. Accordingly, the speed reduction, additional resistance or slamming, which are caused by the large amplitude of ship motions, should be restricted completely. The objective of this study is

the conceptual design of oceangoing large fast ship, which has 40 knots speed, 5,000-10,000 tons payload, especially has the good sea-keeping quality such as no speed reduction and absolutely no slamming in the waves of sea state 7 (with significant wave height of 6-9 meters).

In this study, a “Resonance-Free SWATH (RFS)” ship is introduced as an example of the oceangoing large fast ship. Some results of experiments and theoretical predictions regarding the motion responses of RFS in waves using small controllable fins are presented. First, theoretical estimation and experiments of PD control for RFS’s motion are

discussed. Where P indicates the proportional control action and D denotes the derivative control action. Secondly, the results of motion responses of RFS in regular head waves are compared with other hull forms such as mono-hull, ordinary SWATH or trimaran.

2 CONCEPTUAL DESIGN OF RFS

2.1 Design policy of the ship form

Comparing the motion amplitude between ships with and without restoring force or moment, it is recognized that the latter has no resonant peak and its response amplitude is smaller than the former as shown in Figure 1. The ship without restoring moments, especially in the case of pitching, can be realized by means of extremely small water plane area compared with ordinary SWATH as shown in Figure 2. Consequently, the ship has no resonance in pitch response, which is called as a “Resonance-Free SWATH (RFS)” in this study.

2.2 Summary of conceptual design for RFS

The overall appearance of the conceptual design^{1), 2)} for RFS is shown in Figure 3.

The resistance components of the ship are estimated as follows: Frictional resistance is determined by using Schoenherr’s coefficient for equivalent plate. Wave making resistance is estimated by means of Michell’s thin ship theory for the strut and singularity distribution method for the lower hull. Viscous pressure resistance is considered as correction term from real ship data. As a result, total resistance of the ship equals 810 tf.

The calculation concerning the structural strength is principally carried out under the condition of regular wave with a wave height of 10.8 m. This is equivalent to the 1/1000 maximum expected value of the sea state with a significant wave height of 6 m. Head and beam seas are selected as the wave directions. Normal and shear stress acting on the three parts, i.e. the strut end of the lower hull (the root of the overhang portion of the lower hull), the upper deck connection (central cross section of the upper deck) and the connecting part between the upper deck and the strut, are calculated respectively. Wave loads such as pitch moment, yaw moment, split force and split force moment are considered as the external load condition in the strength calculation. According to the calculation, the maximum principal stress is 24.4 kgf/mm², which is well within the acceptable limits for a high strength steel of 70 kgf/mm² yield strength, where the

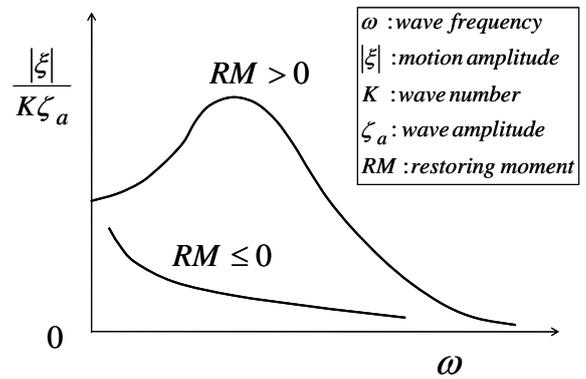


Figure 1 Resonance Amplitude Operator (RAO)

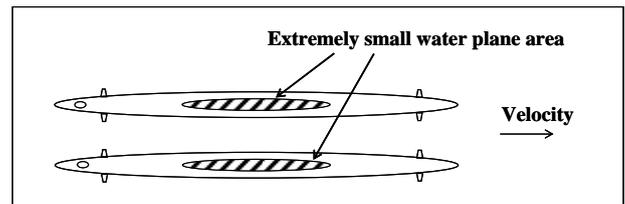


Figure 2 Water plane area of RFS

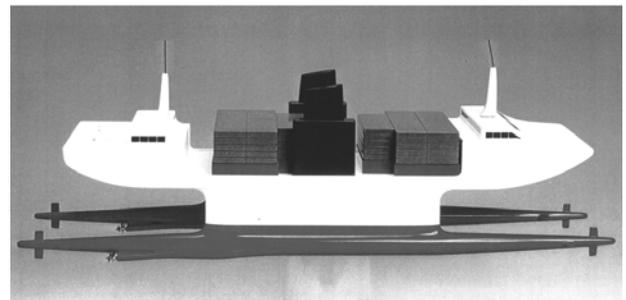


Figure 3 Overall appearance of RFS

Table 1 Principal particulars of RFS

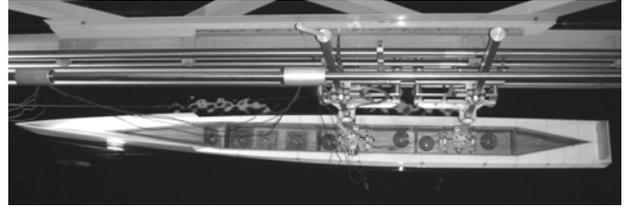
Displacement tonnage : 24,000 t
Light weight : 10,367 t
Power plants : 3,157 t
Dead weight : 13,633 t
Lighter : 1,000 t
Payload : 5,400 t, 540 containers (40 ft)
Fuel : 6,833 t
Upper hull : length:200 m, breadth:55 m
Lower hull : length:230 m, maximum diameter:8.85 m
Strut : length:90 m, maximum breadth:4.425 m
Draft : 12.85 m
Speed : 40 knots
Resistance : 810 tf
Main engine : 8 Gas turbines (44,000 Ps), Total 352,000 Ps
Propulsion : 8 Contra-rotating propellers
Cruising distance : 4,800 nautical miles (Pacific Ocean)
Controlling fin : 8 Fins, Total fin area 160 m ²

$$\left\{ \begin{aligned}
A_{F33} &= A_{F33f} + A_{F33a} \\
&+ \frac{1}{\omega} \left(\frac{1}{2} \rho A_f U C_{L\alpha 3f} C_{s3f} + \frac{1}{2} \rho A_a U C_{L\alpha 3a} C_{s3a} \right) \\
&= A_{33wif} - A_{33wof} \\
B_{F33} &= \frac{1}{2} \rho A_f U C_{L\alpha 3f} C_{c3f} + \frac{1}{2} \rho A_a U C_{L\alpha 3a} C_{c3a} \\
&= B_{33wif} - B_{33wof} \\
A_{F53} &= -A_{F33f} \ell_f - A_{F33a} \ell_a \\
&- \frac{1}{\omega} \left(\frac{1}{2} \rho A_f U \ell_f C_{L\alpha 3f} C_{s3f} + \frac{1}{2} \rho A_a U \ell_a C_{L\alpha 3a} C_{s3a} \right) \\
&= A_{53wif} - A_{53wof} \\
B_{F53} &= -\frac{1}{2} \rho A_f U \ell_f C_{L\alpha 3f} C_{c3f} - \frac{1}{2} \rho A_a U \ell_a C_{L\alpha 3a} C_{c3a} \\
&= B_{53wif} - B_{53wof}
\end{aligned} \right. \quad (5)$$

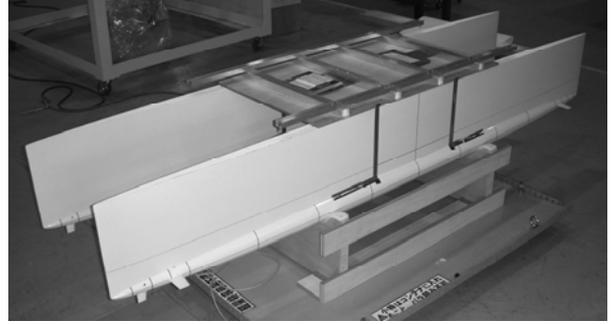
$C_{L\alpha 3f} C_{c3f}$, $C_{L\alpha 3f} C_{s3f}$ and $C_{L\alpha 3a} C_{c3a}$, $C_{L\alpha 3a} C_{s3a}$ can be obtained from equation (5). On the other hand, in the case of pitch motion,

$$\left\{ \begin{aligned}
A_{F55} &= A_{F33f} \ell_f^2 + A_{F33a} \ell_a^2 \\
&+ \frac{1}{\omega} \left(\frac{1}{2} \rho A_f U \ell_f^2 C_{L\alpha 5f} C_{s5f} + \frac{1}{2} \rho A_a U \ell_a^2 C_{L\alpha 5a} C_{s5a} \right) \\
&+ \frac{1}{\omega^2} \left(\frac{1}{2} \rho A_f U^2 \ell_f C_{L\alpha 5f} C_{c5f} + \frac{1}{2} \rho A_a U^2 \ell_a C_{L\alpha 5a} C_{c5a} \right) \\
&= A_{55wif} - A_{55wof} \\
B_{F55} &= \frac{1}{2} \rho A_f U \ell_f^2 C_{L\alpha 5f} C_{c5f} + \frac{1}{2} \rho A_a U \ell_a^2 C_{L\alpha 5a} C_{c5a} \\
&- \frac{1}{\omega} \left(\frac{1}{2} \rho A_f U^2 \ell_f C_{L\alpha 5f} C_{s5f} + \frac{1}{2} \rho A_a U^2 \ell_a C_{L\alpha 5a} C_{s5a} \right) \\
&= B_{55wif} - B_{55wof} \\
A_{F35} &= -A_{F33f} \ell_f - A_{F33a} \ell_a \\
&- \frac{1}{\omega} \left(\frac{1}{2} \rho A_f U \ell_f C_{L\alpha 5f} C_{s5f} + \frac{1}{2} \rho A_a U \ell_a C_{L\alpha 5a} C_{s5a} \right) \\
&- \frac{1}{\omega^2} \left(\frac{1}{2} \rho A_f U^2 C_{L\alpha 5f} C_{c5f} + \frac{1}{2} \rho A_a U^2 C_{L\alpha 5a} C_{c5a} \right) \\
&= A_{35wif} - A_{35wof} \\
B_{F35} &= -\frac{1}{2} \rho A_f U \ell_f C_{L\alpha 5f} C_{c5f} - \frac{1}{2} \rho A_a U \ell_a C_{L\alpha 5a} C_{c5a} \\
&+ \frac{1}{\omega} \left(\frac{1}{2} \rho A_f U^2 C_{L\alpha 5f} C_{s5f} + \frac{1}{2} \rho A_a U^2 C_{L\alpha 5a} C_{s5a} \right) \\
&= B_{35wif} - B_{35wof}
\end{aligned} \right. \quad (6)$$

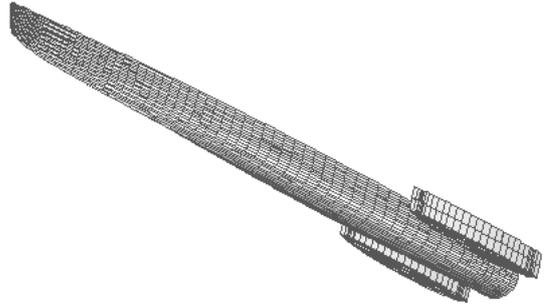
In a similar way, $C_{L\alpha 5f} C_{c5f}$, $C_{L\alpha 5f} C_{s5f}$ and $C_{L\alpha 5a} C_{c5a}$, $C_{L\alpha 5a} C_{s5a}$ are obtained. Here mass of fin and viscous force due to fin are neglected. A_{ijwif} , B_{ijwif} or A_{ijwof} , B_{ijwof} denote added mass, damping coefficient of RFS with fins or without fins, respectively. A_{ijwif} , B_{ijwif} or A_{ijwof} , B_{ijwof} can be calculated by using 3D Green function method or Rankine panel method, and also can be measured by experiments.



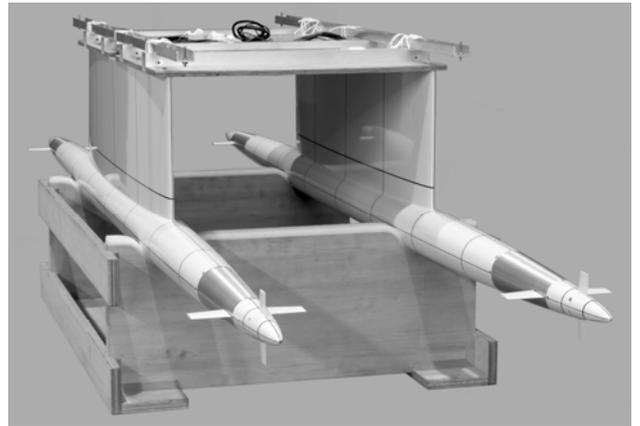
(a) Mono-hull



(b) Ordinary SWATH



(c) Trimaran



(d) RFS

Figure 4 General view of four kinds of hull forms

4 EXPERIMENTS

4.1 Models of four hull forms

Table 2 Principal particulars of four models

	Mono-hull	Ordinary SWATH	Trimaran	RFS
L (m)	2.5	2.0	2.5	2.0
B (m)	0.192	0.486	0.192	0.486
d (m)	0.064	0.112	0.064	0.112
l_{cb} (%)	+ 8.96	0	---	0
A_w (m ²)	0.3503	0.1208	---	0.0473
KG (m)	0.084	0.189	---	0.189
GM _L (m)	8.607	1.480	---	- 0.028
κ_{yy}/L	0.192	0.228	---	0.211
ρV (kg)	14.71	18.68	---	15.49
U (m/s)	2.476	1.918	2.476	1.918
F_n	0.50	0.433	0.50	0.433

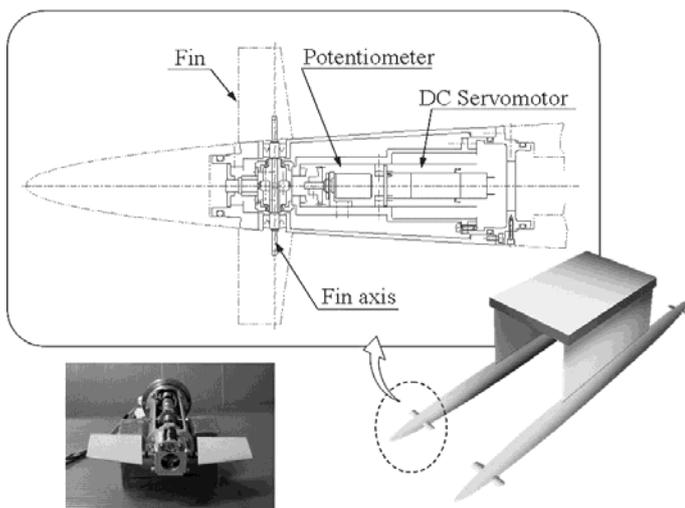


Figure 5 Plan of controllable fins installed in RFS model

Experiments to compare motion responses in waves among four hull forms, i.e. mono-hull, ordinary SWATH, trimaran and RFS, are carried out in model basins.

The general view of four ship models is shown in Figure 4.

Also principal particulars of these four models are shown in Table 2 with items of length L , breadth B , draught d , longitudinal center of buoyancy l_{cb} , water plane area A_w , height of gravity center KG, longitudinal metacentric height GM_L, radius of gyration κ_{yy}/L , mass ρV , advancing speed U or Froude number F_n where ρ indicates density of water and V denotes displaced volume of the model. The detail of experiments is as discussed in the previous study⁵⁾. Ordinary SWATH and RFS have the same lower hulls but different strut length and consequently different parameters of A_w , GM_L, ρV and so on. The strut length of RFS is equal to 0.783 m, approximately one third of the strut length 2.0 m of ordinary SWATH. So, RFS model has negative

restoring moments because of the extremely small water plane area.

4.2 Experiments of controllable fins

Assembling drawing of movable fins is shown in Figure 5. Four controlling equipments of fins are installed in the bow and stern ends of both lower hulls, with a diameter of about 40 mm. Controlling equipment consists of DC servomotor, worm gear, fin axes and potentiometer principally. The attack angle of four pairs of movable fin equipment can be controlled independently. Maximum amplitude of attack angle of each fin is designed as 20 deg, maximum frequency of fin oscillation equals 3.0 Hz. The instructed value $\alpha_{cf,a}$ of fin attack angle is calculated according to equation (7).

$$\alpha_{cf,a} = \alpha_{c3f,a} \mp \alpha_{c5f,a} = \frac{K_{D3}\dot{z} + K_{P3}z}{4\rho AC_{L\alpha}U^2} \mp \frac{K_{D5}\dot{\theta} + K_{P5}\theta}{4\ell_0\rho AC_{L\alpha}U^2} \quad (7)$$

where the right-hand side of equation (7) is - at fore fin (abbreviated as f) or + at aft fin (abbreviated as a), $C_{L\alpha}$ indicates lift-curve slope ($=3.12$ 1/rad^{3, 4)}) and ℓ_0 denotes moment lever of fin ($=0.8333$ m).

Phase lag of fin control system between the output value of potentiometer (feedback heave or pitch signal) and the output value of fin actuator (actual attack angle) are measured. The result in the case of 1.105 Hz (corresponds to $\lambda/L=2.00$) equals about 26 deg. Phase lag of 26 deg is equivalent to time constant of about 0.07 sec in control system.

4.3 Experiments of PD control

According to findings from previous study²⁾, minimum P gain constant and maximum D gain constant should be adopted for the PD control of RFS motions.

Impulse response experiments of RFS model with controllable fins running at $F_n=0.43$ are carried out in still water to obtain the maximum stable gain. The discriminant for the maximum stable D gain is performed systematically. The model starts to run at a pitch attitude of $\theta=+$ or -2 deg. During the tests, it is checked whether the model can be controlled well and the horizontal attitude can be kept when running at $F_n=0.43$. In practice, the failure of control system is not only the problem of divergence but also includes the hunting problem, i.e. a phenomenon relating to the high oscillation of control fins. Consequently, the maximum stable D gain is usually decided at the turning point of hunting.

4.4 The maximum stable gain for ordinary SWATH and RFS

5 RESULTS AND DISCUSSION

5.1 Effect of D gain on motion responses

First, the experimental results regarding the effect of D gain constant on motion responses of ordinary SWATH are shown in Figure 7. The gain constants tested in experiments are listed in Table 4. In the table OGA, OGC2 and OGC indicate gain rate 0.6, 0.8 and 1.0 respectively. The experiments in the case of OGC2 or OGC are carried out in spite of attack angle fluctuations. The abbreviation Ord stands for ordinary SWATH with fixed fins which is not controlled by PD and the symbol Cal denotes the calculated results by means of strip method in the figure. It is observed that the heave and pitch motion responses of ordinary SWATH is reduced considerably by using D control gain and the effect of that is saturating near gain OGA, and also phase differences of each experiment agree well with each other.

Secondly, the experimental results regarding the effect of D gain constants on motion responses of RFS are shown in Figure 8 and the gain constants tested are listed in Table 5. In the table, GB, GA and GC denote gain rate 0.5, 1.0 and 1.2 respectively. Also the experiments in the case of GC are carried out in spite of attack angle fluctuations. It can be seen that there exists obviously the effect of D gain on the reduction of heave and pitch motion responses, and the effect of that is saturating near gain GA. Moreover, the result that phase differences of each experiment agree well with each other shows that experiments are carried out with high accuracy.

5.2 Effect of P gain on motion responses

The experimental results regarding the effect of P gain constants on motion responses of RFS are shown in Figure 9 and the gain constants tested are listed in Table 6 where GD2, GDF or GD3 has the P gain constant of 2.0, 2.4 or 3.0 fold the P gain constant of GA. It can be seen that there is no effects of P gain constant on the heave and pitch motion responses in the figure.

Accordingly, it is understood that the policy to adopt the PD gain constants described previously, i.e. minimum P gain and maximum D gain should be selected, is correct.

5.3 Motion responses in regular head waves

Experimental results of heave and pitch motion responses of four hull forms advancing in regular head waves are presented in Figure 10. Gains of OGA for ordinary SWATH and GA for RFS are

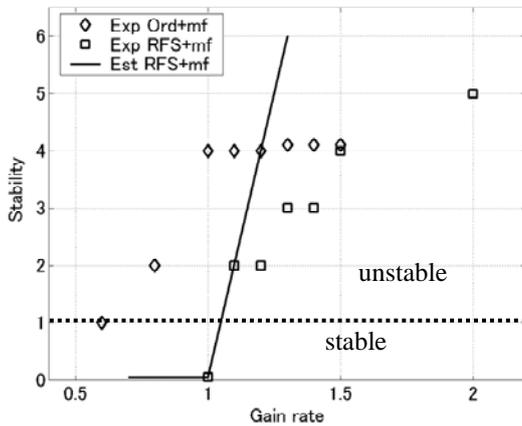


Figure 6 Maximum stable gain rate for ordinary SWATH and RFS

Table 3 Gain constants for ordinary SWATH and RFS

	Heave		Pitch	
	K_{P3} (kg/s ²)	K_{D3} (kg/s)	K_{P5} (kgm ² /s ²)	K_{D5} (kgm ² /s)
Ord+OGA	0	128.4	0	67.2
RFS+GA	0	214	99	112

Results of experiments and theoretical estimations of discriminant⁽⁶⁾ are shown in Figure 6. The abscissa of gain rate indicates magnification ratio of fundamental D gain constant as shown in Table 3, which is defined as gain GA, while the ordinate denotes control stability as described above and the value greater than 1.0 means that control system is unstable. From Figure 6, it can be seen that experimental results agree well with theoretical estimation and the maximum stable gain rate is determined as 1.0, i.e. gain GA, for RFS.

Gain rate 1.0 for RFS is determined as described above, on the other hand, maximum stable gain rate 0.6 for ordinary SWATH is selected as shown in Figure 6 as the result of the same experiments as RFS. The reason to choose different values of gain rate, i.e. 1.0 and 0.6 for these two hull forms, arises from that the energy accumulated by the attack angle of fin is dissipated easily in the case of RFS because of the large damping coefficients of ship hull compared with those of ordinary SWATH. In the experiments of motion responses, fundamental PD gain constants adopted for ordinary SWATH or RFS are as shown in Table 3. In the table, OGA, in which D gain rate equals 0.6, indicates the gain constants for ordinary SWATH while GA, in which D gain rate is 1.0, denotes the gain constants for RFS, where P gain constant of pitch motion for ordinary SWATH is adopted as $K_{P5}=0$ because ordinary SWATH has enough positive restoring moments.

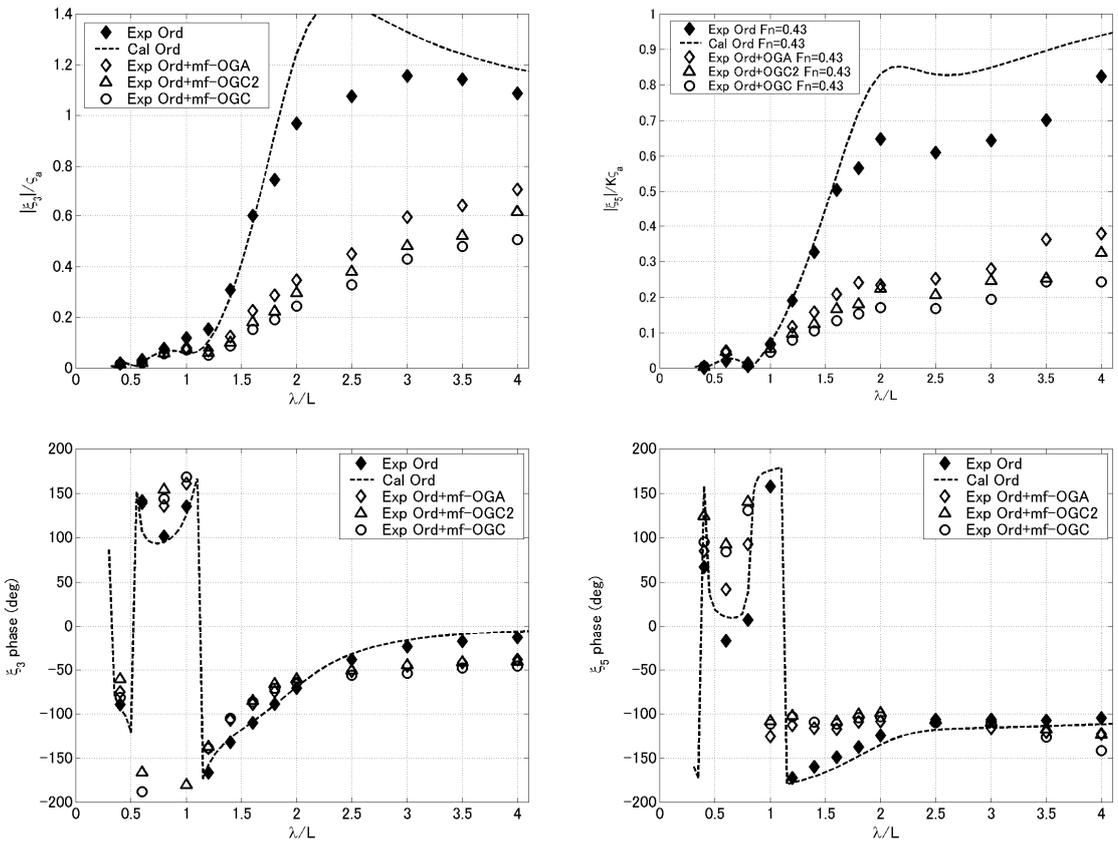


Figure 7 Effect of D gain constant on motion responses of ordinary SWATH in regular head waves ($F_n=0.43$)

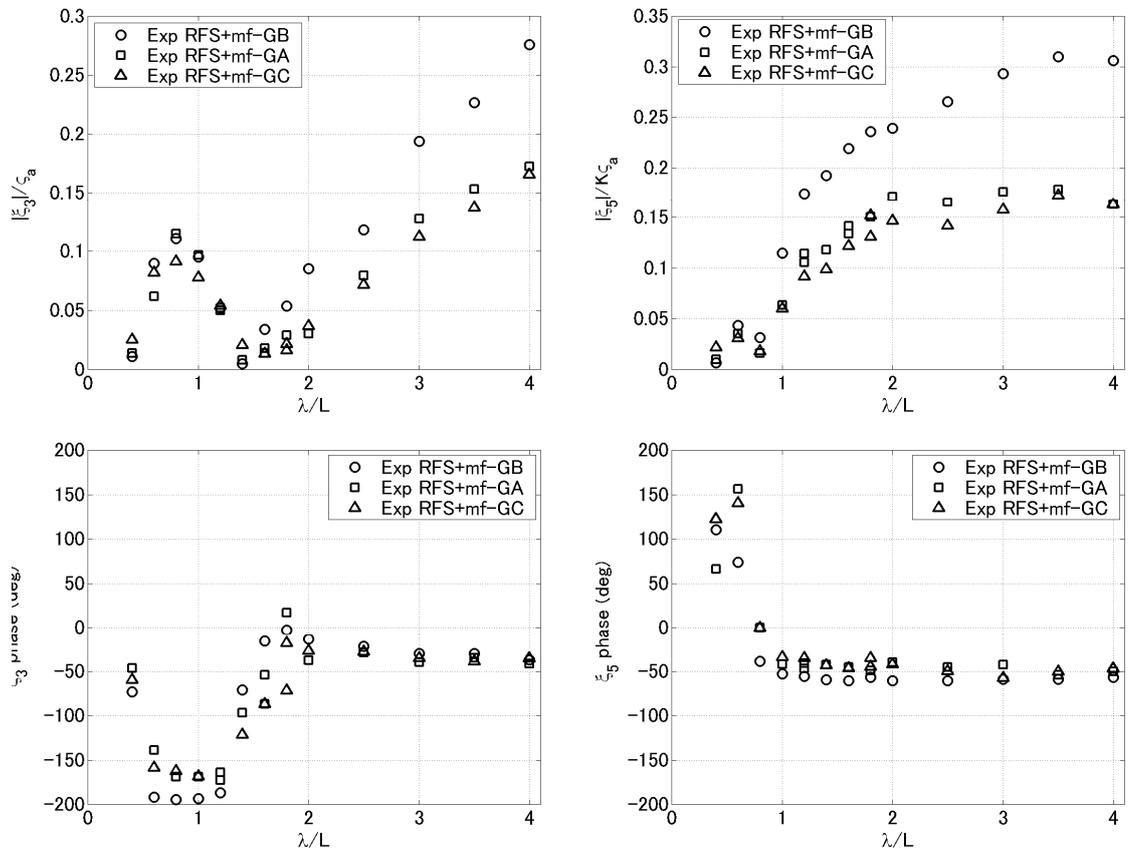


Figure 8 Effect of D gain constant on motion responses of RFS in regular head waves ($F_n=0.43$)

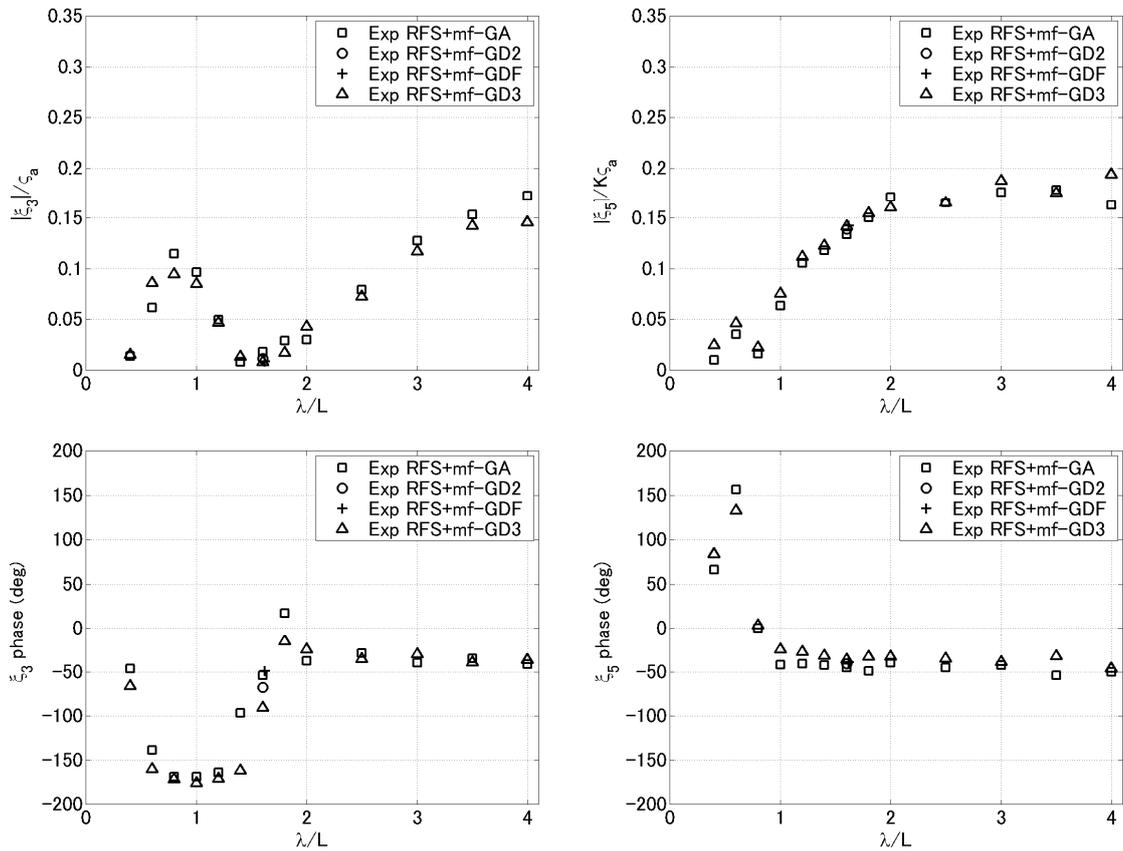


Figure 9 Effect of P gain constant on motion responses of RFS in regular head waves ($F_n=0.43$)

adopted in experiments. Calculated results for mono-hull and theoretical results for RFS by the use of RNM are also plotted in the same figure, where RNM indicates that the hydrodynamic coefficients and wave exciting forces used in the motion equations of theoretical study are renormalized from the experimental measurement. In addition, the typical wave spectrum at North Atlantic Ocean in winter is plotted, where the ordinate of spectrum indicates the density of occurrence probability of waves with significant wave height more than 6 m. First, it can be seen that calculated or theoretical results and experimental results agree very well with each other.

Secondly, in comparison among mono-hull, trimaran and RFS, heave and pitch motion responses of RFS are significantly smaller than those of mono-hull or trimaran. Although Froude numbers for these hull forms are a little different from each other, the tendency of the magnitude of motion responses can be compared qualitatively. It can be observed that resonant peaks obviously exist in motion responses of mono-hull, trimaran or ordinary SWATH while there is no resonance in the case of RFS.

Thirdly, in comparison between ordinary SWATH and RFS, i.e. the same SWATH models with different strut length, it is observed that motion responses of RFS are much smaller in heave motion while are smaller in pitch motion than those of

Table 4 D gain constant for ordinary SWATH

	Heave		Pitch	
	K_{P3} (kg/s ²)	K_{D3} (kg/s)	K_{P5} (kgm ² /s ²)	K_{D5} (kgm ² /s)
Ord+mf-OGA	0	128.4	0	67.2
Ord+mf-OGC2	0	171.2	0	89.6
Ord+mf-OGC	0	214	0	112

Table 5 D gain constant for RFS

	Heave		Pitch	
	K_{P3} (kg/s ²)	K_{D3} (kg/s)	K_{P5} (kgm ² /s ²)	K_{D5} (kgm ² /s)
RFS+mf-GB	0	107	99	56
RFS+mf-GA	0	214	99	112
RFS+mf-GC	0	256.8	99	134.4

Table 6 P gain constant for RFS

	Heave		Pitch	
	K_{P3} (kg/s ²)	K_{D3} (kg/s)	K_{P5} (kgm ² /s ²)	K_{D5} (kgm ² /s)
RFS+mf-GA	0	214	99	112
RFS+mf-GD2	0	214	198	112
RFS+mf-GDF	0	214	235	112
RFS+mf-GD3	0	214	297	112

ordinary SWATH. The difference between the motions of ordinary SWATH and RFS may attribute to the advantages of RFS such as no resonant

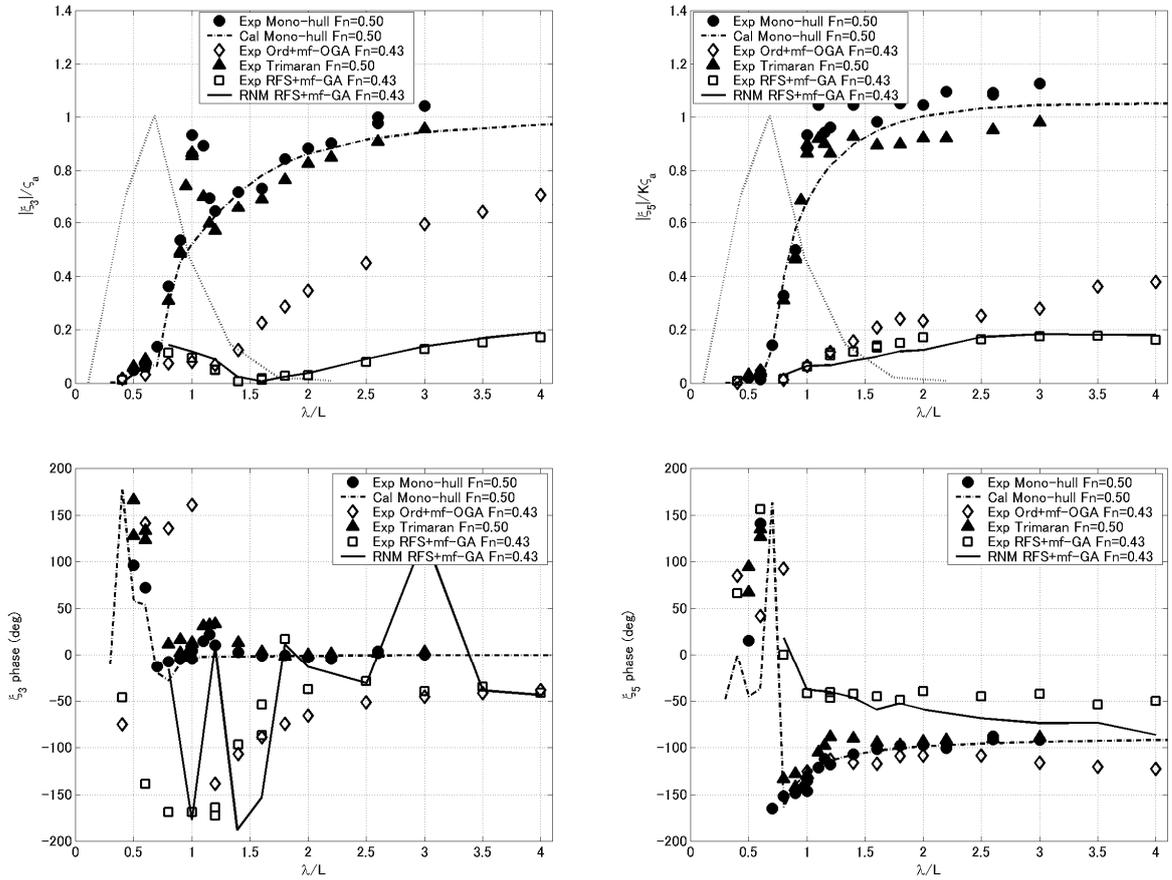


Figure 10 Motion responses of four kinds of hull form in regular head waves

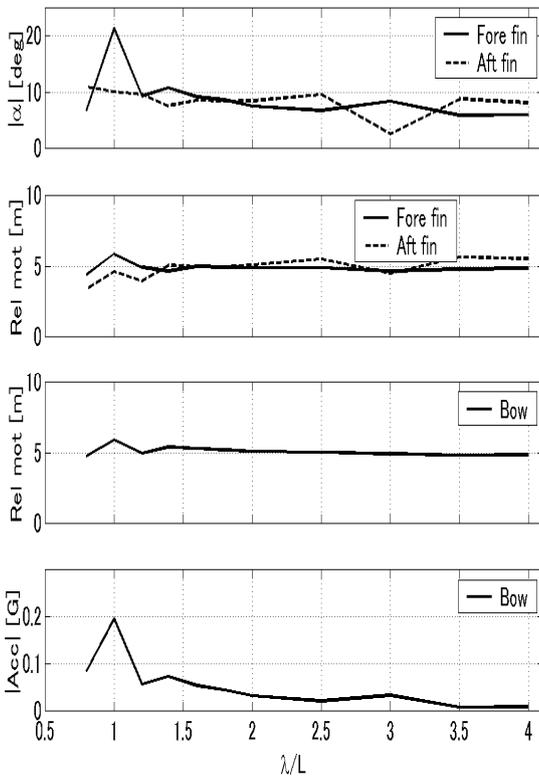


Figure 11 Seakeeping properties of RFS running at 40 knots in regular head waves with 8 m wave height

peak, small wave exciting forces, large damping coefficients of hull and large D gain can be adopted for RFS.

5.4 Seakeeping properties of RFS

Theoretical estimation of seaworthiness properties for real RFS running at 40 knots in regular head waves with 8 m wave height is presented in Figure 11. The figures are numbered from the top. The first figure shows amplitude of attack angle of fore or aft fin. The results of those are less than 10 deg i.e. less than stall angle except for the case of $\lambda/L=1.0$. The second or third figure shows relative motion between fin or bow and wave surface. It can be seen that relative motion is ensured sufficiently small in big waves with 8 m height so that no slamming or propeller racing happens. The fourth figure shows vertical acceleration of bow. It is observed that the acceleration is less than 0.1 G.

6 CONCLUSIONS

First, theory of PD control to reduce motion responses of RFS significantly is devised. Regarding PD control of RFS's motions by the use of fin lift, motion equations are formulated to

include controlling forces due to fin lift, unsteady characteristics of fin lift generation, interaction among fins and lower hulls and time lag of control system. Theoretical calculations and experiments to measure motion responses of RFS running at $F_n=0.43$ in regular head waves using proper control gain constants are carried out. Theoretical and experimental results agree well with each other. Accordingly, theoretical method to predict the stability of control system and motion responses is reliable.

Secondly, the comparison of motion responses in regular head waves among four hull forms such as mono-hull, trimaran, ordinary SWATH and RFS is carried out. Where the motions of RFS and ordinary SWATH are controlled by the use of PD control. As the result, motion responses of RFS are significantly reduced compared with those of mono-hull, trimaran or ordinary SWATH. Then, it can be concluded from the results of theoretical estimations and the experiments that RFS shows very good seaworthiness.

7 ACNOWLEDGEMENTS

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8 REFERENCES

- 1) **Yoshida, T., Fujita, Y. and Fujino, M.** (2000) *A proposal of the CS-Swath as a Transocean High Speed Ship, Transactions of RINA, Vol.142 (B), 136-149, 2000.*
- 2) **Yoshida, M., Kihara, H., Iwasita, H., Itakura, H., Bao, W. and Kinoshita, T.** (2009) *On the resonance-Motion-Free SWATH (RMFS) as an oceangoing large fast ship, OMAE2009-79103.*
- 3) **Lee, C. M. and Curphey, M.** (1977) *Prediction of motion, stability, and wave load of Small-Waterplane-Area Twin-Hull Ships, SNAME Transactions, vol. 85, 94-130.*
- 4) **Pitts, W. C., Nielsen, J. N. and Kaattari, G. E.** (1959) *Lift and center of pressure of wing-body-tail combinations at subsonic, transonic, and supersonic speeds, National Advisory Committee for Aeronautics, Report 1307.*
- 5) **Yoshida, M., Kihara, H., Iwashita and Kinoshita, T.** (2009) *On the resonance-Motion-Free SWATH as an oceangoing large fast ship, International conference on innovation in high speed marine vessels, 31-38.*
- 6) **Yoshida, M., Kihara, H., Iwashita and Kinoshita, T.** (2011) *Motion control of Resonance-Free SWATH using small movable fins, International Conference High Speed Marine Vessels, 106-118.*