Model Experiments on Extreme Motions of a Wave-Piercing Tumblehome Vessel in Following and Quartering Waves

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Summary

This paper reports model experiments of a wave-piercing tumblehome hull in following and quartering waves for examining the applicability of a system-based simulation model proposed by the authors to stability of an unconventional ship. In captive model experiments, the wave-induced surge force and roll restoring moment were measured and confirmed that conventional hydrodynamic prediction methods are applicable. In free-running model experiments, broaching and stable surf-riding were frequently realised. Here the maximum roll angle due to the severe yaw motion is about 70 degrees. The existing simulation model is compared with these experiments. The comparison shows that the current simulation well estimates boundary between the oscillatory motion and non-oscillatory ones such as surf-riding and broaching but it underestimates the yaw motion and overestimates the roll motion.

1. Introduction

Ship stability criteria have been empirically or semi-empirically developed so far. Applicability of such criteria to unconventional vessels could be limited because of no sufficient data exist for unconventional vessels so that empirical criteria could make designing new-ship types unnecessarily difficult. Therefore, the International Maritime Organization started to develop performance-based intact stability criteria for unconventional passenger and cargo ships, as well as the US Navy and Royal Navy for war ships.[1)] Here a first-principle tool such as numerical simulation or model experiment is requested to directly assess intact stability in place of prescriptive criteria. Although conventional vessels complying with current intact stability criteria such as Rahola's criteria and/or weather criterion are sufficiently safe against capsizing under intact conditions, unconventional vessels could occasionally face danger of capsizing through dynamic ship behaviours, such as broaching in following and quartering waves. For dangerous phenomena in following and quartering waves, several numerical models were developed and some of them were well validated with free-running model experiments.[1-2)] The subject ships used in these validation studies include containerships, fishing vessels, destroyers and so on. These have rather conventional hull forms so that validation studies with unconventional vessels are highly expected.

Responding to this situation, the authors attempt to execute free-running model experiment of an unconventional vessel in following and quartering waves in order to provide experimental data for validation of numerical models. Recently, as a typical unconventional vessel, the geometry of a wave-piercing tumblehome vessel was published by the US Office of Naval Research (ONR) for research purposes. Although a conventional ship usually has flare at the bow and wall-sided section in the midship, this unconventional vessel, known as the ONR tumblehome vessel, has inversely inclined bow and tumblehome sections above calm water plane. The choice of tumblehome or flare had been a problem in ship design from the sailing ship era, and is closely relevant to ship stability. From a pure hydrostatic viewpoint, the tumblehome is less attractive because slope of the righting arm decreases with increasing the heeling angle. Dynamic behaviours of the tumblehome, however, have not yet been sufficiently investigated with latest naval architecture and the conclusion only with hydrostatics is not guaranteed to be final. Therefore, the ONR tumblehome vessel is a good example of unconventional vessels to be used for validation of intact stability simulation model.

In this paper, as a first step of this validation studies with the ONR tumblehome vessel, captive and free-running model experiments of the ONR tumblehome vessel are reported and comparisons between these and the existing simulation models validated for some conventional vessels are provided.

2. Captive Model Experiments for Hydrodynamic Forces

Most of existing simulation models utilised system-based approaches where hydrodynamic forces acting on the hull should be estimated in advance as functions of ship motions. In other words, applicability of simulation model depends on the prediction accuracy of hydrodynamic forces. Thus, the authors conducted captive model experiments of the ONR tumblehome vessel. Her principal particulars and body plan are shown in Table 1 and the Fig.1, respectively. As can been in Fig.2, two coordinate systems are used: wave fixed with origin at a wave trough, ξ axis in the direction of wave travel; and body fixed with origin at the centre of gravity, the x axis pointing towards the bow, the y axis to starboard and the z axis downwards. Here u is the ship velocity in the x direction; v is the ship velocity in the y direction; ζ_G is the heave; θ is the pitch angle; ξ_G is the longitudinal position of the centre of gravity from a wave trough and the heading angle from the wave direction is χ.

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The experiment was executed in the towing tank at Osaka University with a 1/48.94 scaled model of the ONR tumblehome vessel. Here the model is free in heave and pitch, and was attached with the towing carriage via the 4 component dynamometer, which detects the surge and sway forces and the roll and yaw moments. The heave and pitch were measured by a potentiometer and a gyroscope, respectively. The model was towed with a constant velocity in a regular wave train generated by a plunger-type wave maker. The pitch radius of gyration is different from the standard value but the effect of it in the experiment cannot be so large because of the low encounter frequency.

Table 1 Principal particulars of the ONR tumblehome model used in the captive model experiments

Items	*Ship*	*Model*
Length : *L*	154.0 m	3.147 m
Breadth : *B*	18.78 m	0.384 m
Depth : *D*	14.5 m	0.296 m
Draught : *d*	5.494 m	0.112 m
Displacement : *W*	8507 ton	72.6 kg
Block coefficient : C_b	0.535	0.535
Radius of gyration in pitch: K_{yy}/L	0.25	0.212

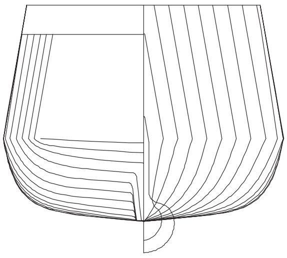

Fig.1 Body plan of the ONR tumblehome vessel

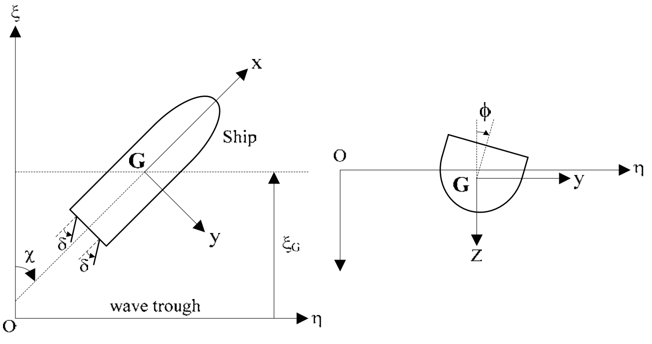

Fig.2 Coordinate systems

2. 1 Wave-induced surge force

The wave-induced surge force is responsible for surf-riding. Thus, it is necessary to accurately evaluate it for realising a quantitative prediction of ship behaviours in following and quartering waves. The wavelength to ship length ratio were 1.25 and the wave steepness were 1/50, 1/33.3 and 1/20. This wave-induced surge force can be calculated as the linear Froude-Krylov force as the first-order approximation, which well explains the wave-induced surge force for a small trawler up to the wave steepness of 1/10[3] and for a purse seiner at least with small wave steepness [4]. The measured results are compared with the Froude-Krylov calculation as shown in Fig. 3. Here the wave-induced surge force, X_W, is normalised with

$$X'_W = X_W / \left(W \cdot H / \lambda\right) \tag{1}$$

where *W*: the ship displacement, *H*: the wave height and λ: the wavelength. The comparison indicates that the wave-induced surge force has an almost linear relationship with the wave steepness and the linear Froude-Krylov calculation significantly overestimates the experiment when the Froude number is smaller than 0.2. The Froude number of 0.2 coincides with the Hanaoka parameter, $\tau = U\omega_e/g$, of 0.25 where *U*: the ship forward velocity, ω_e: encounter frequency of a ship to waves and *g*: gravitational acceleration. Here, in a unsteady potential flow theory with linear free-surface condition, the velocity potential relating to symmetric motions diverges.[5] When the Hanaoka parameter increases by increasing the forward velocity, the Froude-Krylov prediction provides better agreement. Thus, improvement of the prediction could be made by investigating an unsteady wave making phenomenon as one of future tasks.

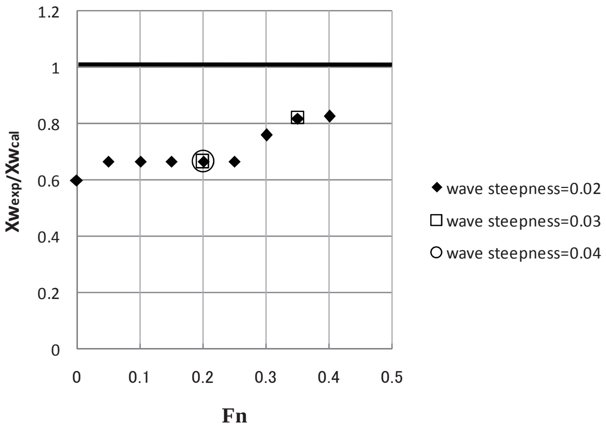

Fig.3 Comparisons of amplitude of wave-induced surge force between the experiment and the linear theory. Here λ/L=1.25 and different wave steepness

2. 2 Roll restoring moment

It is important to estimate the roll restoring variation in waves for accurately predicting parametric rolling and loss of stability on a wave crest. For this purpose, the model was towed with heel angles of 0, 10 and 20 degrees. The resulting roll moment around the centre of ship's gravity, *K*, was used to calculate the metacentric height variation due to waves, ΔGM, as follows:

$$\Delta GM = \frac{-K}{W\sin\phi} \qquad (2).$$

This was fitted with the following formula as a function of the relative position of the ship to waves.

$$\Delta GM = GM_m + GM_1 \cos\{2\pi(\xi_G/\lambda - \varepsilon_1)\}$$

$$+GM_2\cos\{4\pi(\xi_G/\lambda-\varepsilon_2)\} \qquad (3)$$

where GM_m: the mean of the GM variation, GM_1 and GM_2: the amplitudes of the first and second harmonic components of GM, respectively, ε_1 and ε_2: the phase lags of the first and second harmonic components of GM, respectively. As an example, the experimental result for the wavelength to ship length ratio of 1.25 was plotted in Figs.4-8, and shows that the metacentric height variation is roughly proportional to the wave steepness and it has minimum when the ship centre situates near a wave crest. In addition, the mean and the second harmonic are not much smaller than the harmonic component.

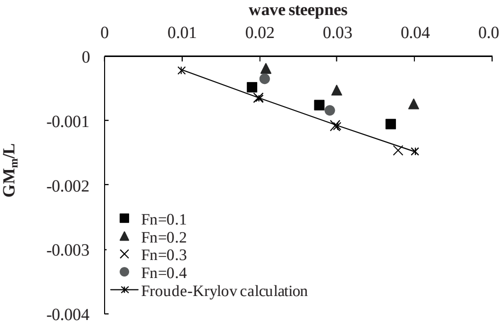

Fig.4 Mean of the metacentric height variation with λ/L=1.25 in following seas

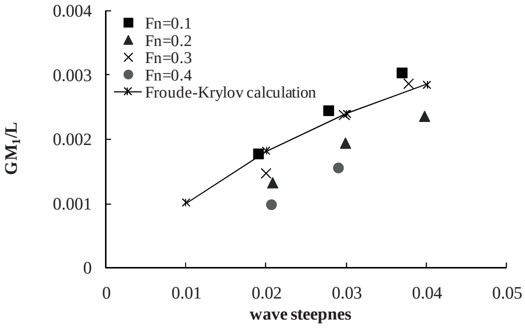

Fig.5 Amplitude of 1st harmonics of the metacentric height variation with λ/L=1.25 in following seas

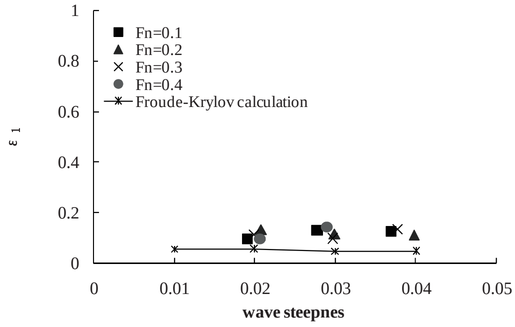

Fig.6 Phase lag of 1st harmonics of the metacentric height variation with λ/L=1.25 in following seas

The restoring variation can be calculated with the Froude-Krylov calculation for conventional ships.[6] Here the incident wave pressure is integrated around the wetted hull surface up to the wave surface and a ship is free in heave and pitch. Thus the calculated value does not depend on the Froude number. The calculated value is compared with the above measured one, as shown in Fig. 9. It is found that the Froude-Krylov calculation roughly agrees with the experiment at least for the Froude number of 0.3 also for this unconventional vessel. The comparisons between experiment and the Froude-Krylov calculation in Figs. 4-8 shows that good agreement is not always provided for other Froude numbers and the metacentric height variation does not simply change with the Froude number. This suggests that the metacentric height variation could have radiation and diffraction components for a lower speed region and hydrodynamic lift component for a higher speed region as discussed by the authors[7].

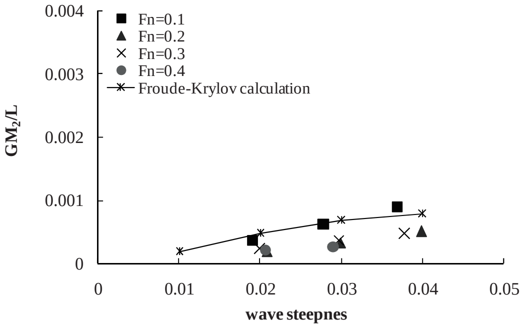

Fig.7 Amplitude of 2nd harmonics of the metacentric height variation with λ/L=1.25 in following seas

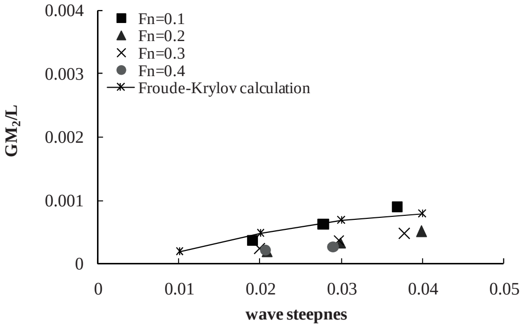

Fig.8 Phase lag of 2nd harmonics of the metacentric height variation with λ/L=1.25 in following seas

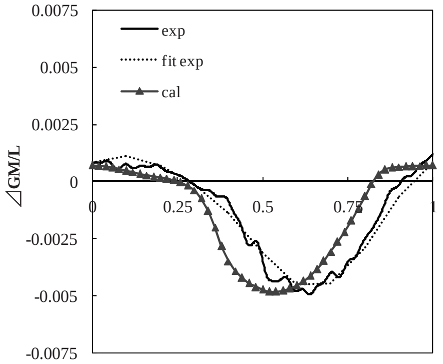

Fig.9 Comparison in metacentric height variation between the experiment and the Froude-Krylov calculation with λ/L=1.25, H/λ=0.04 and Fn=0.3 in following seas

3. Free-running model experiment

For more directly assess stability, free-running model experiments were executed with the scaled model in a seakeeping and manoeuvring basin at National Research Institute of Fisheries Engineering. The basin is 60 m long, 25 m wide and 3.2 m deep. The model dimensions used here and its righting arm curves are shown in Table 2 and Fig. 10, respectively. Two loading conditions were tested: one is critical to the Sarchin and Goldberg criteria[8)] and the other is slightly below them. The angles of vanishing stability under these loading conditions are 180 degrees so that capsizing cannot appear. This is because the superstructure of the ONR tumblehome vessel is large enough as shown in Fig. 11. The model was propelled with two propellers. Their power was supplied from solid batteries inside the model. A feedback control system was provided to keep the propeller rate constant. The model was equipped with a fibre gyroscope, a computer and steering gears, and a proportional auto pilot for course keeping was simulated within the onboard computer by using the yaw angle obtained from the gyroscope. The roll angle, pitch angle, yaw angle, rudder angle and propeller rate were recorded by the onboard computer. Water surface elevation was also measured by a servo needle wave probe attached to the towing carriage of the basin near the wave maker.

The experimental procedure for following and quartering waves is as follows. First, the model is kept near the wave maker without propeller revolution. Next, the wave maker starts to generate regular waves. After a generated water wave train propagates enough, a radio operator suddenly requests the onboard system to increase the propeller revolution up to the specified one and makes the automatic directional control active. Then the model automatically runs in following and quartering seas to attempt to keep the specified propeller rate and auto pilot course. When the model approaches the side wall or the wave-absorbing beach, the automatic control is interrupted by the radio operator and the propeller is reversed to avoid collision. This is based on the ITTC (International Towing Tank Conference) recommended procedures on model test of intact stability registered as 7.5-02-07-04.1. Throughout this paper, the specified propeller rate is indicated by the nominal Froude number, F_n, which is the Froude number when the ship runs in otherwise calm water with that propeller rate.

In the experiment, the nominal Froude numbers are 0.25, 0.30, 0.35, 0.40 and 0.45, the auto pilot courses, χ_c, are -5, -15, -22.5, -30, -37.5 degrees from the wave direction, the wavelength to ship length ratios are 1.0, 1.25, 1.5, 1.75 and 2.0 and the wave steepness are 1/100, 1/50, 1/33.3, 1/25, 1/16.7 and 1/12.5. In total, about 200 model runs were conducted.

The model runs for the wavelength to ship length ratio of 1.25 and 1.5, and the wave steepness of 1/20 with the GM of 2.068 m in full scale are overviewed in Figs. 12-15 as examples. The first two figures show qualitative natures of the model runs and the others show the maximum roll angle during the model runs. Surf-riding occurs above the Froude number of 0.3 near following waves but the critical speed for surf-riding increases with increasing the auto pilot course. While stable surf-riding appears in smaller heading, broaching is observed in larger heading. If stable surf-riding occurs, the model does not suffer heavy rolling. These are similar to the free-running model experiments for a fishing vessel known as the ITTC Ship A-2[9)]. Although the ITTC Ship A-2 capsizes due to broaching, the ONR tumblehome vessel does not. The maximum roll angle with the GM of 2.068 m is 71.0 degrees at the auto pilot course of -22.5 degrees. Because of large superstructure, however, the model can re-right after such heavy roll. And during the model runs with such large roll angle, one of two propellers and one of two rudders can be temporarily emerged out of water. It is noteworthy here that bow submergence was observed during stable surf-riding, but it did not induce bow-diving or plough-in, thanks to its wave-piercing bow.

Table 2 Principal particulars of the ONR tumblehome model used in the free-running model experiments.

Items	*Ship*	*Model*
Length : L	154.0 m	3.147 m
Breadth : B	18.78 m	0.384 m
Depth : D	14.5 m	0.296 m
Draught : d	5.494 m	0.112 m
Displacement : W	8507 ton	72.6 kg
Block coefficient : C_b	0.535	0.535
Longitudinal position of centre of buoyancy from midship : LCB	2.587 m aft	0.053 m aft
Metacentric height : GM	i)1.781 m ii) 2.068 m	i) 0.0364 m ii) 0.0423 m
Natural roll period : T_φ	i) 12.38 s ii) 11.68 s	i) 1.77 s ii) 1.67 s
Radius of gyration in pitch : K_{yy}/L	i) 0.25 ii) 0.25	i) 0.254 ii) 0.246
Rudder area : A_R	28.639 ㎡ ×2	0.012 ㎡ ×2
Maximum rudder angle: δ_{MAX}	±35°	±35°

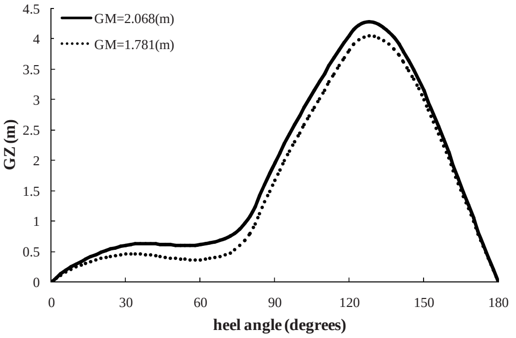

Fig.10 GZ curves of the subject ship

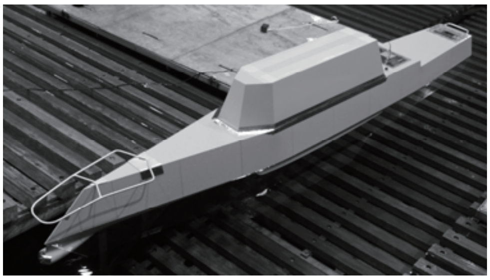

Fig.11 photo of the used ship model

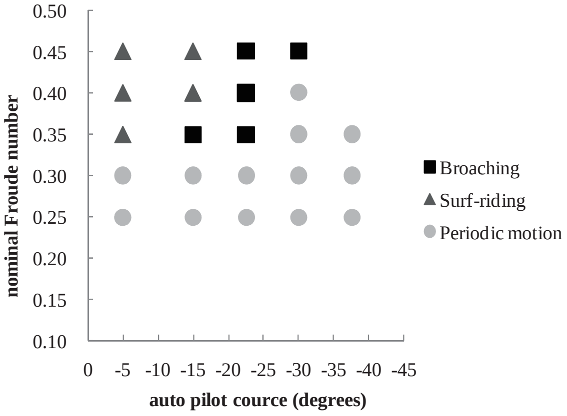

Fig.12 Ship motion modes with H/λ=1/20, λ/L=1.25 and GM=2.068(m)

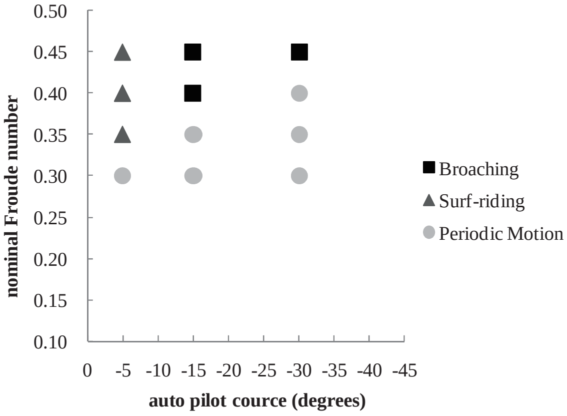

Fig.13 Ship motion modes with H/λ=1/20, λ/L=1.5 and GM=2.068(m)

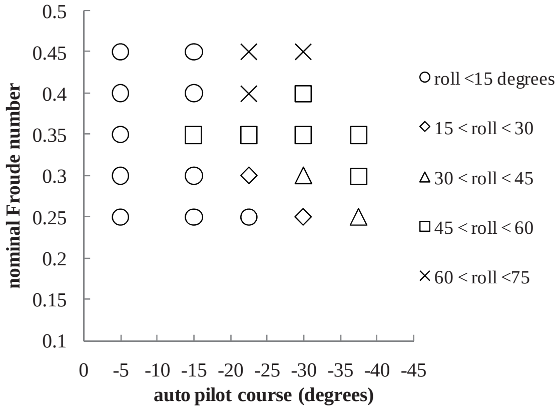

Fig.14 Maximum Roll angle with H/λ=1/20, λ/L=1.25 and GM=2.068(m)

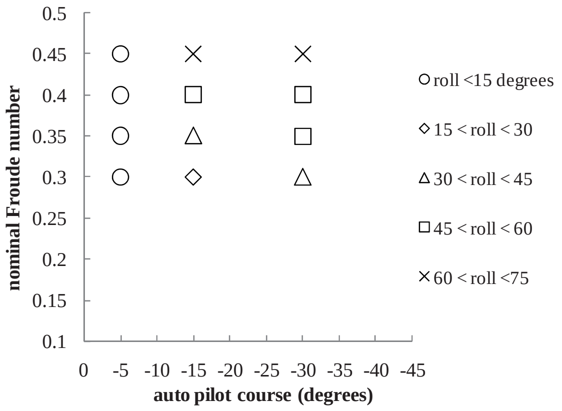

Fig.15 Maximum Roll angle with H/λ=1/20, λ/L=1.5 and GM=2.068(m)

Typical time series among the model runs are shown in Figs. 16-18. Fig. 16 shows the case of periodic motion where the wavelength to ship length ratio of 1.25, the wave steepness of 1/20, the nominal Froude number of 0.30, the auto pilot course of -22.5 degrees and GM of 2.086 m in full scale. Whenever a ship is overtaken by a wave crest, the roll angle of nearly 20 degrees develops. It can be observed that the surge velocity becomes maximum when the ship centre situates on a wave crest, where the roll restoring moment is reduced. Fig. 17 shows the case of broaching where the wavelength to ship length ratio of 1.25, the wave steepness of 1/20, the nominal Froude number of 0.35, the auto pilot course of -22.5 degrees and GM of 2.086 m in full scale. After some oscillatory motions, the model is captured by a wave downslope because the pitch angle is negative and almost constant. Then the course deviation exponentially increases with time despite the opposite application of rudders due to the proportional autopilot. When the rudder angle reaches its limit, the yaw angular velocity further increases in the opposite direction. Thus, this can be identified as broaching. And the roll angle increases in the direction of the centrifugal force due to uncontrolled yaw. Fig. 18 shows the case of stable surf-riding where the wavelength to ship length ratio of 1.25, the wave steepness of 1/20, the nominal Froude number of 0.40, the auto pilot course of -5.0 degrees and GM of 2.086 m in full scale. In this case, the model is also captured by a wave down slope, but the pitch, roll and yaw rate tend to be constant due to the small auto pilot course.

4. Comparison with Numerical Simulation

To compare with the free-running model experiments, an existing mathematical model for a twin-screw and twin-propeller ship, that was proposed by Umeda et al 10), is applied to the ship, operational and environmental conditions used in the experiments. The mathematical model is based on coupled surge-sway-yaw-roll manoeuvring one with linear wave forces calculated by a slender body theory with a low encounter frequency assumption3). The hydrodynamic interactions between ship motions and waves, including the restoring variations, are ignored as higher order terms.1) Since the wave forces are functions of the relative ship position to waves, the mathematical model is nonlinear. Here the manoeuvring and propulsion coefficients in calm water are estimated with the conventional captive model tests for this mathematical model such as the circular motion test.

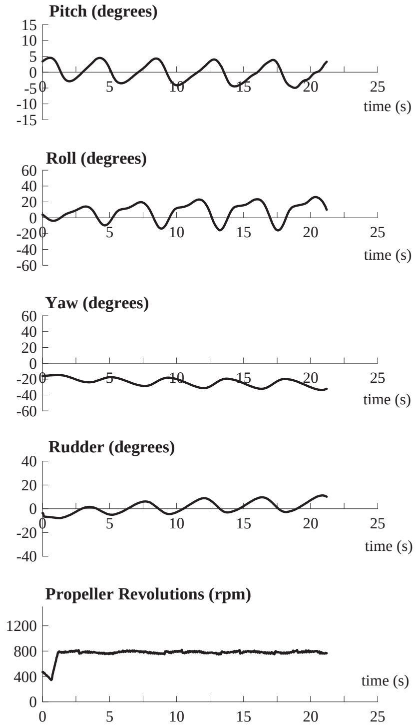

Fig.16 Time series of a periodic motion case with GM=2.068m, H/λ=1/20, λ/L=1.25, F_n=0.30 and χ_c=-22.5 degrees

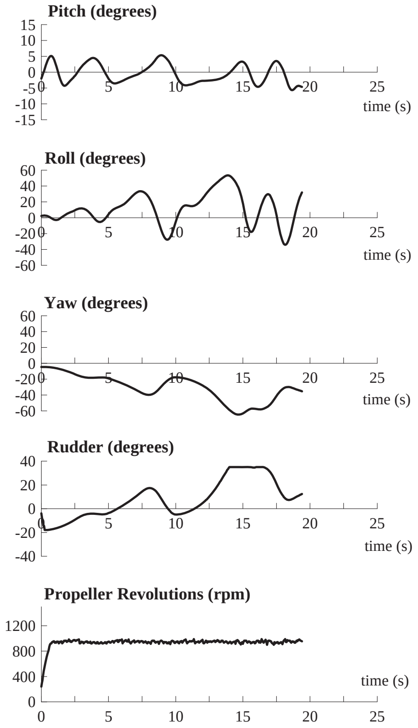

Fig.17 Time series of a broaching case with GM=2.068m, H/λ=1/20, λ/L=1.25, F_n=0.35 and χ_c=-22.5 degrees

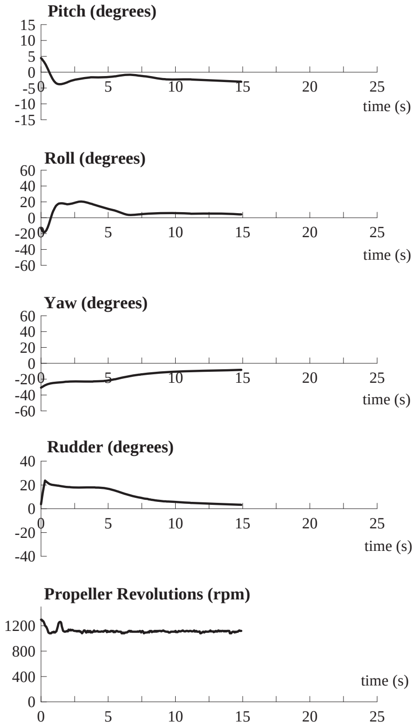

Fig.18 Time series of a stable surf-riding case with GM=2.068m, H/λ=1/20, λ/L=1.25, F_n=0.40 and χ_c=-5.0 degrees

As already mentioned, it is desirable to examine effects of the emergence of propeller and rudder in mathematical modelling. In this paper, however, the existing mathematical model is applied to the ONR tumblehome vessel without any correction as a preliminary study. A systematic numerical simulation was executed for a dense grid of operational parameters with GM of 2.068 m, the wavelength to ship length ratio of 1.25 and the wave steepness of 1/20. The initial state used here is a periodic state under the nominal Froude number of 0.1 and the auto pilot course of 0 degrees from the wave direction. Then the operational parameters are suddenly changed to the specified values, similar to the free-running model experiments. The result is shown with the experimental data in Fig. 19. When the auto pilot course is smaller, there is a boundary between the stable surf-riding and periodic motions near the nominal Froude number of 0.3. Below this boundary, periodic motions are simulated as they are identified in the experiments. Above this boundary, a stable surf-riding region exists, and includes the stable surf-riding identified in the experiment. However, this region also includes the case of broaching in the experiment. When the auto pilot course is larger, the simulated roll exceeds 90 degrees above the nominal Froude number of 0.3. On the other hand, in the experiment the maximum roll angle is 71 degrees. This means that the mathematical model overestimates the roll angle and underestimates the yaw deviation. It can be presumed that this is induced by the emergence of propeller and rudder out of water, which could reduce the yaw checking ability under the extreme roll angle. Improving mathematical modelling with these elements is the future task

The same mathematical model but for a single-screw and single-rudder ship was applied to the fore-mentioned ITTC A-2 Ship as a conventional ship, and larger discrepancy between the

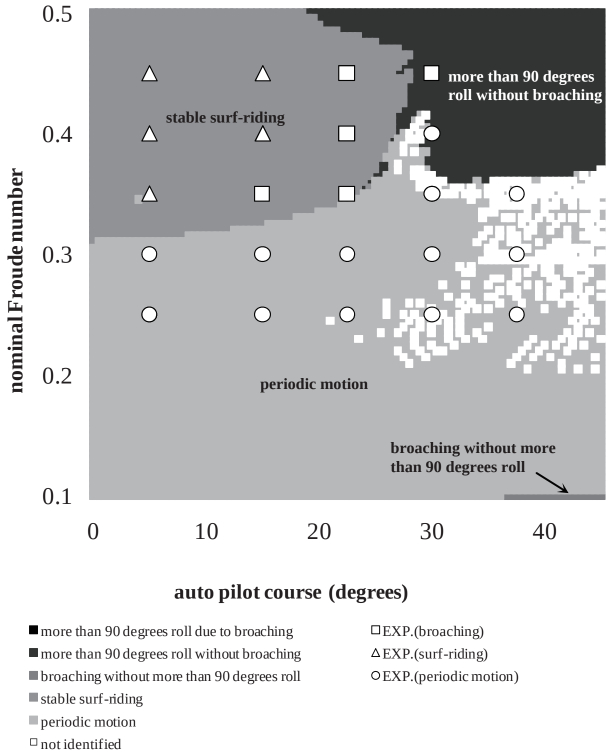

Fig.19 Comparison between the experimental results and numerical results with GM=2.068m, H/λ=1/20 and λ/L=1.25

calculation and experiment was reported. 9) This is partly because the wave steepness used here is smaller than that used for the ITTC A-2 Ship, i.e. the wave steepness of 1/10. The reason why high steepness was used for the ITTC A-2 Ship is that a dangerous phenomenon occurs only with such high wave steepness. This means that the ONR tumblehome vessel is more susceptible to dangerous phenomena in following and quartering waves.

5. Concluding Remarks

The captive and free-running model experiments for the ONR tumblehome vessel in following and quartering waves were executed and their data were provided for validation of mathematical modelling. The ONR tumblehome vessel complying with the current prescriptive criteria can suffer extreme roll angle up to 71 degrees when her nominal Froude number is larger than the surf-riding threshold. Typical broaching was recorded but does not result in capsizing because the angle of vanishing stability is 180 degrees. The wave-induced surge force and the roll restoring variation can be roughly predicted by the conventional Froude-Krylov calculation at least when the forward velocity is sufficiently high. For more accurate modelling, effect of the emergence of rudder and three-dimensional wave pattern should be investigated for this kind of unconventional vessel.

Acknowledgements

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