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Stability assessment for intact ships in the light of model experiments

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Abstract: A systematic method for assessing intact ship stability with a free-running model in a seakeeping and maneuvering basin is proposed in this paper. Model experiments were carried out in extremely steep regular waves for a model drifting, running in head seas, and quartering seas. This method was applied to two purse seiners, and efficiently identified thresholds in metacentric heights for capsizing of these ships. These capsizing thresholds are compared with requirements of the IMO Code on Intact Stability. This series of model experiments also confirms that capsizing at the threshold occurs only in quartering seas, and shows that capsizing is caused by broaching, loss of stability on a wave crest, or bow diving.

Key words: capsizing, broaching, stability loss, bow diving following seas, quartering seas

Introduction

Although the study of ship dynamics started with this subject, intact ship stability remains an unsolved problem. For example, four capsizing accidents of intact fishing vessels of 20 gross tonnage (GT) or over were reported in Japan during the last decade. To prevent such capsizing, the International Maritime Organization (IMO) and the administrations established intact stability criteria, which are mainly based on comparisons between casualty statistics and hydrostatics or dynamic models for a ship in beam seas. However, these criteria are not adequate as tools for assessing the real stability of a particular ship, because, they were developed more than 40 years ago with statistics from out-of-date ships and without enough physical observations. Therefore, it is desirable to assess the intact stability of a recent ship with physical or theoretical modeling relevant to actual capsizing phenomena.

Several studies have been conducted to realise and observe the capsizing of a free-running model in waves. At the early stage, model experiments were carried out in natural wind waves with manual steering, Despite the difficulty in repeating model runs with constant wave conditions, the experiments showed that a ship capsizes in following and quartering seas more easily than in beam seas and identified several modes of capsizing.[1–3] In the next stage, artificial waves in a seakeeping basin and an autopilot were introduced into stability experiments in order to obtain more quantitative assessments of the effects of design or operational parameters.[4–10]

These experimental projects were conducted for their own purposes: an investigation of the mechanism of capsizing, a validation of the IMO operational guidance, and so on. As a result, a systematic methodology for assessing capsizing thresholds for each ship has not yet been established. On the other hand, because demands for safety have significantly increased recently, there is a need for routine testing of the stability of each ship, just as each ship is routinely tested for propulsion. Each research organization is attempting to assess stability by trial and error. Therefore, it is essential to establish a rational and efficient methodology for assessment of experimental stability as soon as possible.

This paper proposes a methodology for the assessment of intact stability by model experiments, and shows examples of assessment with this methodology for two purse seiners.

Experimental method to assess ship stability

Philosophy of experimental method

So far, capsizing experiments with models have been carried out mainly in irregular waves. Although real

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ocean waves are obviously irregular, experiments with irregular waves should be repeated with many different realizations to obtain statistically meaningful results. The number of realizations increases significantly when the probability of capsizing is reasonably small, as it is for most actual ships. Thus, this kind of experiment is not appropriate for practical purposes. To avoid this difficulty, Takaishi[11] proposed the use of encounter group waves, which can be found when the ship velocity component is nearly equal to the group velocity of the principal wave components, for capsizing experiments in irregular waves as the worst scenario. In this situation, since the encounter wave profile tends to be sinusoidal in time, capsizing experiments in irregular waves can be carried out in a rather deterministic way.

On the other hand, the experimental results up to now have not yet shown clear evidence of a unique mode of capsizing in irregular waves. In most cases, if the maximum amplitude of the wavemaker is limited to a certain value, capsizing in long-crested irregular waves occurs much more easily than in short-crested waves, and capsizing in regular waves occurs much more easily than in irregular waves.[9] Takaishi's proposal is also based on the fact that capsizing due to regular excitation is more dangerous than that due to random excitation. In other words, model experiments in the steepest regular waves may generally overestimate the danger of capsizing in irregular waves or may represent the worst scenario among actual situations. Thus, the use of regular waves is not simply conservative, and we should pay more attention to experiments in regular waves for more efficient and rational assessment of stability.

On the basis of these considerations, we proposed the following experimental plan. First, we carry out capsizing model experiments in extremely steep regular waves. If the model does not capsize, we can presume that the possibility of capsizing for this ship in any irregular waves is negligibly small. If the model capsizes, the possibility of capsizing for this ship in certain irregular waves is unknown. Then, if necessary, we should carry out capsizing model experiments in irregular waves[12] or make assessment based on stochastic theory.[13,14] The experiment in regular waves has an important role to minimize the size of the whole assessment program. In case of relative assessment, critical wave steepness or critical metacentric height for capsizing can be used as an index, and this can be determined with a set of capsizing model experiments in regular waves. Another problem is how to the determine ship speed or heading angle for the experiments. It is widely accepted that the most dangerous operational condition is a run in quartering seas.[1–10] Thus, it is obvious that a model should be tested in quartering seas with lower wave steepness than in beam seas.

Another candidate wave type for stability assessment is concentrated transient waves. The maximum wave slope of these waves can instantaneously and locally exceed the breaking limit of regular waves.[15] Thus the concentrated waves can be more dangerous for ship stability than the steepest regular waves within one or two wave cycles. However, the transient waves are not so appropriate to realize the capsizing of a ship running in following and quartering seas, because it needed more than three encounter cycles in previous model experiments. In other words, a ship capsizing in certain transient waves can capsize in following and quartering seas with smaller metacentric height. Therefore, the use of the steepest regular wave trains is more suitable for stability assessment. Here it is still noteworthy that the transient waves are recommended for a ship often meeting breaking waves or a ship in less danger in following and quartering seas.

Experimental method

The details of our standard test plan are shown in Table 1. (1) First, a model is adjusted to have a specified metacentric height as well as a specified freeboard and gyro radius in pitch or yaw. (2) Then a natural roll period and damping coefficients are measured with roll decay tests. (3) Next, the relationship between the propeller revolution and ship speed is obtained by model runs in still water or by standard propulsion tests. (4) The turning test in still water with the maximum rudder angle and maximum speed is recommended. If the model capsizes, the rudder angle or ship speed should be limited not to capsize only due to a turning motion. (5) The next step is to conduct experiments in regular waves. The wave period is equal to or slightly longer than the natural roll period, and the wave steepness, H/λ, is specified to be 1/7. Because of wave breaking, the measured wave steepness can be smaller than 1/7 but should be larger than 1/10. The model drifts in these waves with an idling propeller. If the hull form is

Table 1. Standard program of capsizing model experiment at NRIFE

1. Preparing model (weighting, ballasting, measuring gyro radius)
2. Inclining test and roll decay test
3. Speed trial in calm water
4. Turning test in calm water
5. Capsizing test without forward velocity in regular waves
6. Capsizing test with forward velocity in regular head waves
7. Capsizing test with forward velocity in regular following/quartering waves

longitudinally symmetric or nearly so, the model meets waves from the side. If the model capsizes, another trial is conducted with sufficiently small wave steepness to find a periodic attractor. It is obvious that a capsizing boundary exists between these two values of wave steepness. Thus, the critical wave steepness for capsizing can be determined within a required accuracy by repeating experimental trials with a regule falsi method, which is often used in the numerical analysis. If the natural roll period is twice as long as the natural heave and pitch period, a similar procedure should be applied for the wave period corresponding to the natural heave and pitch period. (6) Then we may conduct model runs in regular head waves, whose steepness is slightly smaller than the critical one for capsizing with an idling propeller. The wave length to ship length ratio, λ/L, is set at about 1.5, because ship motions become significant in this wave condition.[16] Since the wave steepness is extremely high, the ship speed cannot be so high, even with maximum propeller revolution, and it is not so crucial for capsizing. If we observe capsizing, the critical wave steepness for capsizing in head seas can be determined again with the regule falsi method. (7) Finally, model runs in quartering seas should be commanded. The wave steepness is set to be slightly lower than the critical one for capsizing with an idling propeller. The wave length to ship length ratio should cover the range between 1.0 and 1.5, which is regarded as the worst among Kan's experiments for 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, and 2.25.[8] Until a generated water wave train propagates enough, the model is kept near the wavemaker without propeller revolution. Then, at a certain moment, we command the propeller revolution to immediately increase up to the specified one and the autopilot to be active for the specified course. Repeating these model runs, the critical combination of the nominal Froude number, F_n, and the auto pilot course, χ_c, or the critical wave steepness for capsizing in quartering seas can be identified.

Examples of results with the proposed method

Details of experimental setup

Two Japanese fishing vessels were selected as subjects of the experimental program based on the above method. One is a 1/15 scale model of a 135GT class purse seiner (ship A), and the other is a 1/12.6 scale model of an 80GT class purse seiner (ship B). The general arrangements and principal particulars are presented in Figs. 1 and 2 and Table 2. Assessment of the stability of these purse seiners is an urgent issue, because these types of purse seiners have capsized three times during the last decade in Japan. Both models were

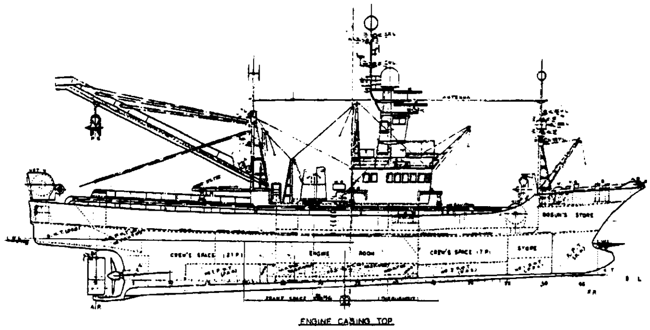

Fig. 1. Ship A

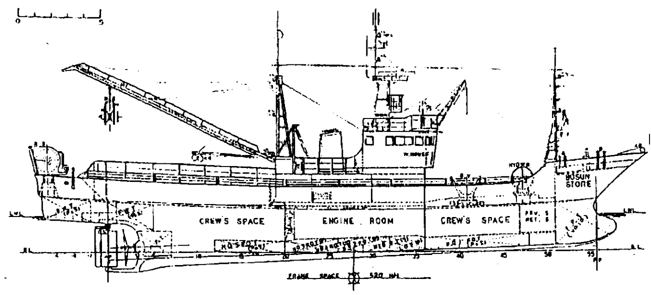

Fig. 2. Ship B

Table 2. Principal particulars of the ships

Feature	Ship A	Ship B
Length overall: L_{OA}	43.0 m	36.5 m
Length between perpendiculars: L_{pp}	34.5 m	29.0 m
Breadth: B	7.60 m	6.80 m
Depth: D	3.07 m	2.60 m
Fore draught: d_f	2.50 m	2.25 m
Mean draught: d_m	2.65 m	2.25 m
Aft draught: d_a	2.80 m	2.25 m
Block coefficient: C_b	0.597	0.577
Prismatic coefficient: C_p	0.769	0.691
Waterline coefficient: C_w	0.985	0.983
Radius of gyration in pitch	0.242 L_{OA}	0.246 L_{OA}
Longitudinal centre of buoyancy aft of midships	1.31 m	0.42 m
Vertical distance between metacenter and keel: KM	4.36 m	3.81 m
Metacentric radius: BM	2.71 m	2.45 m
Rudder area: A_R	3.49 m^2	3.26 m^2
Aspect ratio of rudder	1.84	1.68
time constant of steering gear: T_E	0.63 s	0.63 s
Rudder gain: K_R	1.0	1.0
Maximum rudder rate: δ_{max}	7.5 rad/s	7.5 rad/s
Propeller diameter	2.60 m	2.18 m

Here the steering gear is modeled as follows: $T_E\dot{\delta} + \delta = -K_p(\chi - \chi_c)$ where δ is the rudder angle, $\dot{\delta}$ is the rudder rate, χ is the yaw angle, and χ_c is the autopilot course fitted with forecastle, bilge keels, bulwarks, open freeing ports, and rudders. For ship A, a deck house was not realized on the model as a non-watertight structure, and raised hatches were fitted on the upper deck to store the equipment. For ship B, a deck house was realized without a wheel house, and flat hatches were fitted on the upper deck.

The draught of each model was selected to critically comply with the Japanese Loadline Rule.[17] As shown in Figs. 3 and 4, the metacentric height, GM, was adjusted for several cases. The model of ship A of 1.00 m in GM critically complies with the IMO Code on Intact Stability (IMO IS Code).[18] Here the requirement for the maximum righting lever is the most stringent among several requirements in this code. The model of ship B of 1.65 m in GM critically complies with the IMO IS Code. Here the requirement for the heel angle of the maximum righting lever is crucial. The difference between ship A and ship B in requirements of the IMO IS Code is mainly due to the difference in stern upper deck. If this deck is flat, the code requires larger GM to provide enough righting arm curve. The requirement of the weather criterion included in the IS Code was less stringent for both ships.

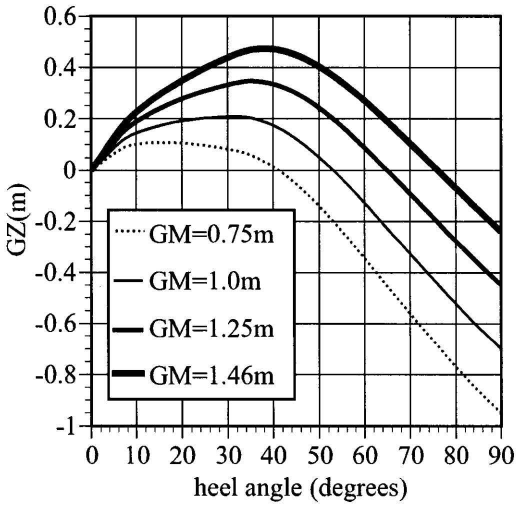

Fig. 3. Restoring moment arm curve of ship A

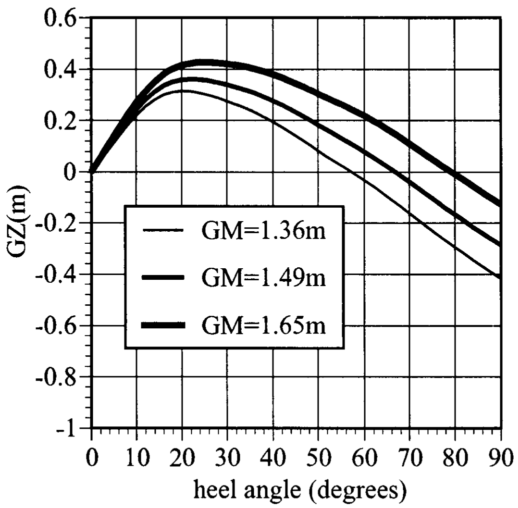

Fig. 4. Restoring moment arm curve of ship B

The models were propelled with electric motors, whose power was supplied by batteries on board with feedback controls of propeller revolution. The designed maximum F_n for each ship was set to be 0.43, defined by the length between perpendiculars. The models were steered by autopilots whose rudder gain was 1. The maximum rudder angle was 35 degrees. Roll, pitch, and yaw angles were detected by fiberoptical gyroscopes. These measured signals as well as the rudder angle and propeller revolution were recorded by on-board computers in a digital form. The measured yaw angle was also used for the autopilot control. Here the adopted reference system and the sign convention are presented in Fig. 5, so that positive pitch is bow up, positive roll results in downward movement of starboard side, positive yaw is to starboard from the wave direction, and positive rudder angle induces positive yaw in calm water. The propeller revolution is indicated by the nominal F_n, which is the F_n when the ship runs in calm water with the specified propeller revolution.

The basin used here is a seakeeping and maneuvering basin of the National Research Institute of Fisheries Engineering (NRIFE). It is 60 m long, 25 m wide, and 3.2 m deep. The wavemaker of this basin consists of 80 plungers driven by digitally controlled electric motors. Although this wavemaker is able to generate even short-crested irregular waves, only regular waves were generated for the experiments described in this paper. The wave length to ship length ratio covers the worst

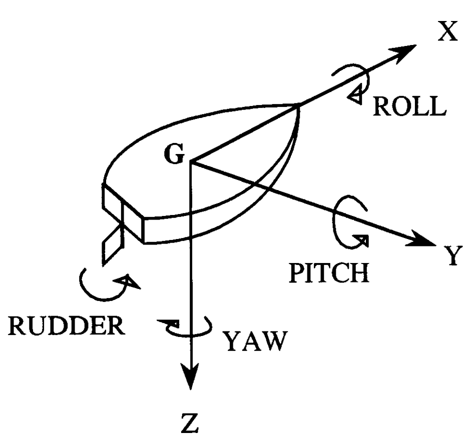

Fig. 5. Reference system

cases for stability, and the wave steepness is the largest for each wave length. For ship A, the wave circular frequencies were specified to realize 1.0, 1.25, and 1.5 in the wave length to ship length ratio with a linear theory. As explained later, the wave length to ship length ratio of 1.25 was the worst in the experiments for ship A. Thus, for ship B, only 1.25 was used. The wave itself was recorded without a ship model by a wave probe fixed at the position 9.5 m from the wave maker. The wave amplitude, a, and the wave circular frequency, ω, were obtained from the time series from the wave probe. Then, considering nonlinearity of the waves,[19] the wave length, λ, was determined with the following formulae:

$$gk\left(1+k^2a^2\right)=\omega^2 \tag{1}$$

$$\lambda = 2\pi/k \tag{2}$$

Here g indicates the gravitational acceleration. As a result, the wave length to ship length ratios and the wave steepness used for the experiments in quartering seas were obtained as shown in Table 3. Significant nonlinear effects exist in the wave length to ship length ratio.

Results and discussion

Ship A. The overview of the experimental results is presented in Table 4. Throughout this paper, all numerical values are in full scale unless specified. This table indicates that the threshold in GM for capsizing of ship A is between 1.25 and 1.46 m. Since the IMO IS Code critically complies with the model of ship A of 1.00 m in GM, this code is not effective for the ship A model.

First, in the tests of hard-over turn with full ahead in calm water, only the case of GM = 0.75 m resulted in capsizing. As the time series shows in Fig. 6, the roll angle exponentially increases from the angle of the maximum righting lever, about 15 degrees, to capsizing. Thus we can conclude that this capsizing is caused by loss of static balance in roll moment. Also, in the experiments of the model without forward velocity, only the case of GM = 0.75 m resulted in capsizing. As shown in Fig. 7, the model gradually heeled due to trapped water on deck and then capsized by loss of static balance. In head seas, the model capsized also in the case of GM = 0.75 m. As shown in Fig. 8, the heeling moment due to trapped water from the bow exceeds the roll restoring moment.

Table 3. Wave parameters used in the experiments in quartering seas

Ship	H/λ	λ/L
A	1/8.7	1.127
A	1/9.3	1.413
A	1/10.0	1.637
B	1/8.8	1.408

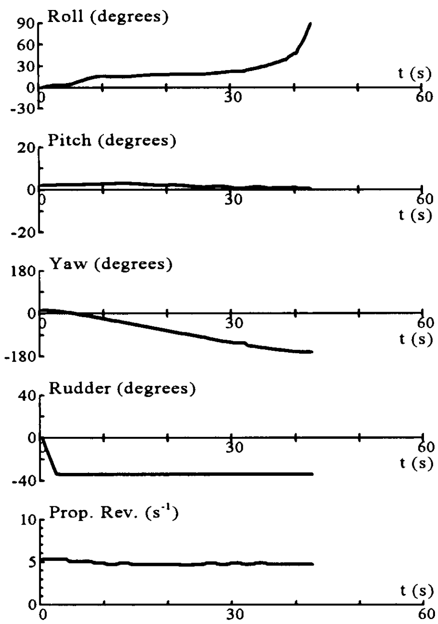

Fig. 6. Time series of capsizing of ship A during turning in calm water with GM = 0.75 m and F_n = 0.35

Table 4. Overview of results for ship A

GM	Turning	Drifting	Head seas	Quartering seas	Natural roll period: T_ϕ	Extinction coefficient: a	Extinction coefficient: b
0.75 m	×	×	×	×	9.7 s	0.041	0.027
1.00 m	○	○	○	×	7.4 s	0.044	0.030
1.25 m	○	○	○	×	5.0 s	0.090	0.028
1.46 m	○	○	○	○	4.6 s	0.150	0.024

○ and × indicate capsizing and noncapsizing, respectively. The extinction coefficients, a and b, are defined as follows: $\delta\phi = a\phi_m + b\phi_m^2$ where $\delta\phi$ and ϕ_m indicate decrement and mean swing angle of roll decay tests without forward velocity, respectively. The virtual roll radius of gyration, $I_{xx} + J_{xx}$, can be calculated as follows: $I_{XX} + J_{XX} = \rho g^2 LBd_m \times C_b \times GM \times T^2_\phi/(2\pi)^2$, where ρ is the water density

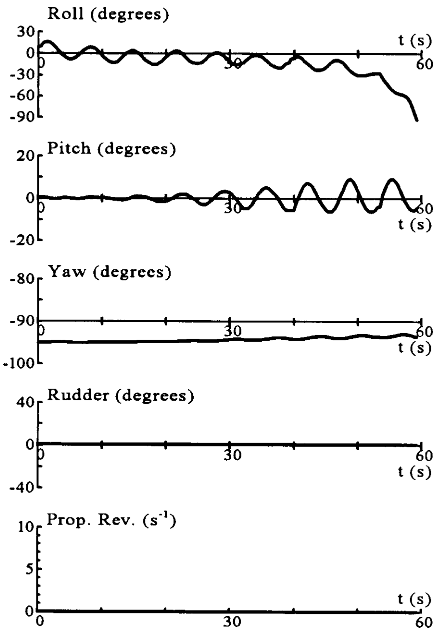

Fig. 7. Time series of capsizing of ship A drifting in waves with GM = 0.75 m, $H/\lambda = 1/8.3$, and $\lambda/L = 1.424$

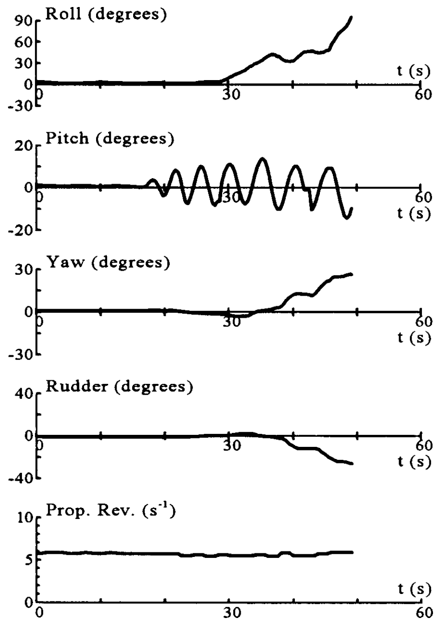

Fig. 8. Time series of capsizing of ship A running in head seas with GM = 0.75 m, $H/\lambda = 1/10.0$, $\lambda/L = 1.637$, $F_n = 0.4$ and χ_c = 180 degrees

For GM = 1.0 m, although no capsizing occurred in turning, drifting, and head seas, the model capsized in quartering seas, as summarized in Fig. 9. Here the model capsized from loss of stability on a wave crest or broaching. Although the autopilot courses were negative throughout this series of experiments, the absolute values of them are indicated in this type of figure. Among three wave length to ship length ratios, the case of 1.25 involves a nonperiodic phenomenon with the lowest nominal F_n. As shown in Fig. 10, the trapped water on deck induced a leeward heel angle and the roll angle increased when a wave crest passed the midship. Since the pitch angle can be approximated by simply tracing a stable equilibrium for a ship running in quartering seas, the zero-upcrossing of the pitch angle indicates the wave crest amidship.[20] Finally, the model capsized at the wave crest amidship. This can be categorized as *capsizing due to loss of stability on a wave crest*, in which the reduced restoring moment at the wave crest amidship cannot counteract the heeling moment due to trapped water on deck.

In an example shown in Fig. 11, the pitch angle tended to a negative constant value after 30 s. This means that the model suffered surf-riding on the downslope. At the same time, the yaw angle violently increased to port and the rudder controlled by the autopilot responded to prevent this yaw motion. However, despite the hard-starboard, the increase in yaw continued for a while. Here the centrifugal force due to large yaw rate, wave-induced force, and rudder force forced the model to roll toward starboard. As a result, the model capsized in this direction. Thus, this is *capsizing due to broaching*.

In the case of GM = 1.25 m, which is larger than the requirement from the IMO IS Code, only one capsizing was observed in quartering seas, as shown in Fig. 12. This capsizing, presented in Fig. 13, was *capsizing due to broaching*. When we further increased GM up to 1.46 m, no capsizing occurred, even in quartering seas, as shown in Fig. 14. However, as indicated in Fig. 15, *broaching without capsizing* was still observed. Here, although the roll angle reached almost 30 degrees, the model did not capsize. As a result of the large yaw angle, the model was overtaken by a wave and then it suffered broaching again. To escape from this chain of broaching, the propeller idling was not effective and full astern immediately after the moment the model was overtaken by a wave crest was necessary in the experiments.

As explained above, ship A can capsize in quartering seas even if it complies with the IMO IS Code. On the other hand, the IMO MSC Circular 707,[21] the guidance for a ship master avoiding danger in following and quartering seas, recommended that the ship master reduces the F_n to 0.3 in heavy following and quartering seas. If the ship complying with the IMO IS Code is operated with this guidance, no capsizing would occur, even in quartering seas.

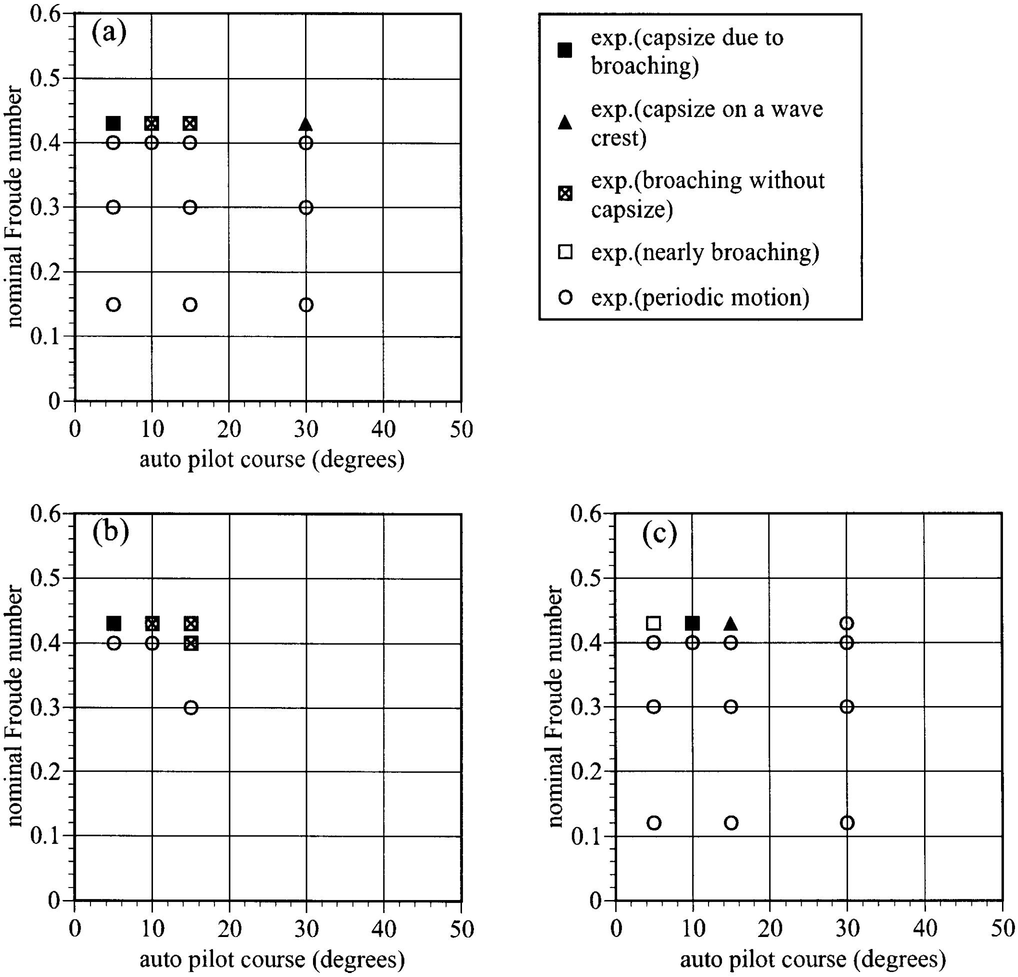

Fig. 9. Results of experiments for ship A running in quartering seas with GM = 1.00 m. **a** $\lambda/L = 1.127$; **b** $\lambda/L = 1.413$; **c** $\lambda/L = 1.637$

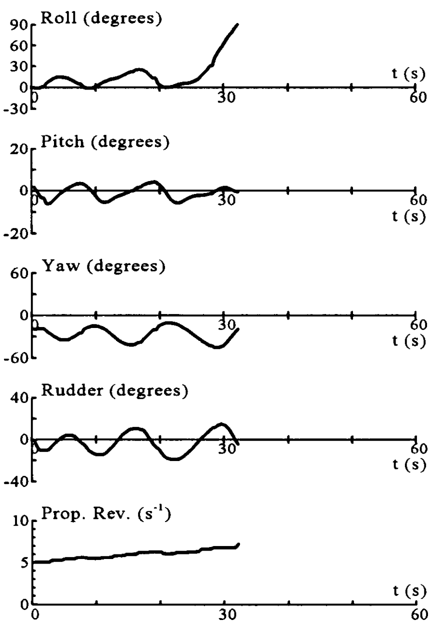

Fig. 10. Time series of capsizing due to loss of stability on a wave crest for ship A with GM = 1.00 m, $\lambda/L = 1.127$, $\chi_c = -30$ degrees, and $F_n = 0.43$

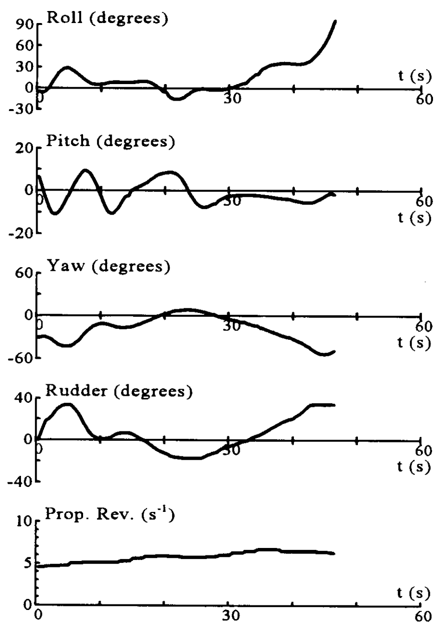

Fig. 11. Time series of capsizing due to broaching for ship A with GM = 1.00 m, $\lambda/L = 1.413$, $\chi_c = -10$ degrees, and $F_n = 0.43$

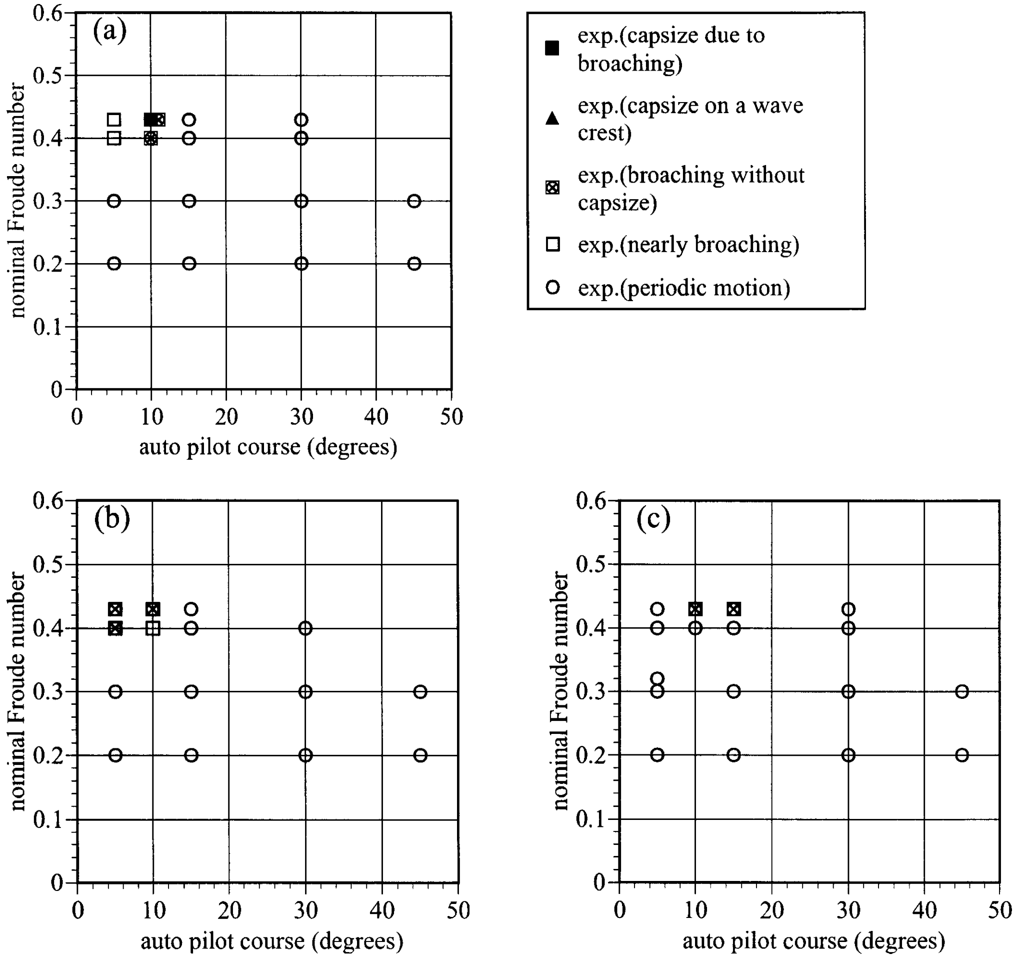

Fig. 12. Results of experiments for ship A running in quartering seas with GM = 1.25 m. **a** $\lambda/L = 1.127$; **b** $\lambda/L = 1.413$; **c** $\lambda/L = 1.637$

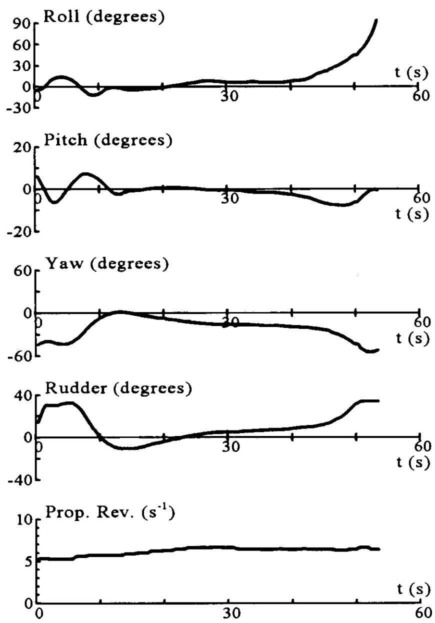

Fig. 13. Time series of capsizing due to broaching for ship A with GM = 1.25 m, $\lambda/L = 1.127$, $\chi_c = -10$ degrees, and $F_n = 0.43$

Ship B. The experimental results for ship B are summarized in Table 5. This indicates that the threshold in GM for capsizing of ship B is between 1.36 and 1.49 m. Since ship B of 1.65 m in GM critically complied with the IMO IS Code, this code slightly overestimates the danger of capsizing for this ship.

No capsizing even for GM = 1.36 m occurred in the experiments in calm water, those without forward velocity, and those in head seas. Considering the results for ship A, the experiments in quartering seas for ship B were carried out under one representative wave condition: $H/\lambda = 1/8.8$ and $\lambda/L = 1.408$.

The experimental results in quartering seas are presented in Fig. 16. Although no capsizing occurred for GM = 1.65 m and GM = 1.49 m, two capsizing were recorded for GM = 1.36 m. One of them is *capsizing due to loss of stability on a wave crest*, as shown in Fig. 17. Although the rudder angle was temporally −35 degrees and at the same time the yaw rate was positive, the yaw acceleration was negative. If we follow the proposal by Renilson,[22] this was not broaching. Finally

Table 5. Overview of results for ship B

GM	Turning	Drifting	Head seas	Quartering seas	Natural roll period	Extinction coefficient: *a*	Extinction coefficient: *b*
1.36 m	○	○	○	×	4.5 s	0.157	0.020
1.49 m	○	□	□	○	4.4 s	0.115	0.027
1.65 m	○	○	□	○	4.1 s	0.141	0.029

○ and × indicate capsizing and noncapsizing, respectively. Since the case with the symbol □ can be logically expected to be noncapsizing, model runs were omitted

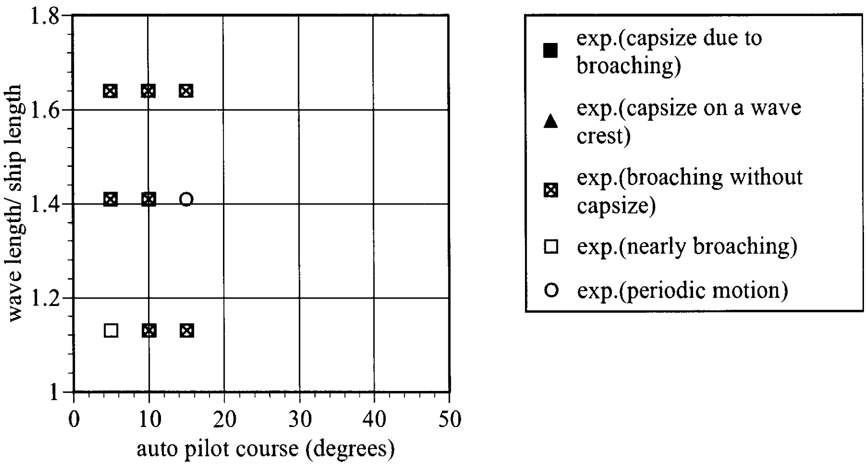

Fig. 14. Results of experiments for ship A running in quartering seas with GM = 1.46 m and $F_n = 0.43$

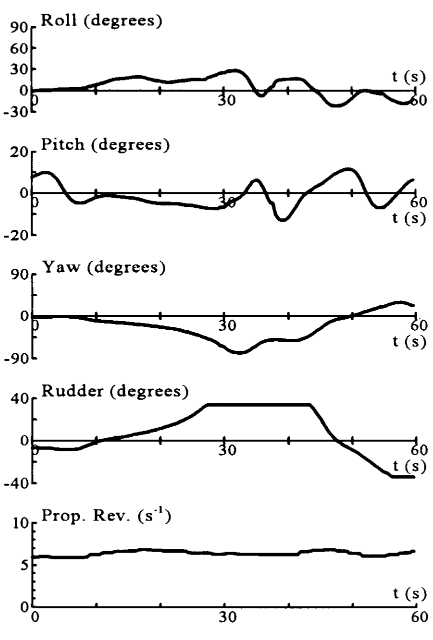

Fig. 15. Time series of broaching for ship A with GM = 1.46 m, $\lambda/L = 1.637$, $\chi_c = -10$ degrees, and $F_n = 0.43$

the model tended to capsize at the zero-upcrossing of the pitch angle, in other words, the wave crest amidship. Then we increased GM by 0.13 m in full scale and repeated the model runs with the same operational parameters. As shown in Fig. 18, no capsizing occurred in this case, but a significant increase in roll was observed whenever a wave crest passed the midship. Thus the threshold was identified for this mode of capsizing.

The other capsizing is presented in Fig. 19. First, the almost constant and zero pitch angle indicates that the model suffers surf-riding on trough. Then the bow dived into the upslope. When the pitch angle reached about –20 degrees, the water plane area decreased due to exposure of the stern. This decrease in the water plane area resulted in the reduction of righting lever and finally capsizing. This mode of capsizing is known for a high-speed craft as *bow diving or plow-in*.[23] The principal trigger of this capsizing here is a high nominal F_n, in other words, large propeller thrust. Because of this, the stable equilibrium in longitudinal force shifted from downslope to trough.[24] Although this nominal F_n is higher than the actual F_n of ship B, future improvement to increase the forward speed for ship B would induce this type of danger.

Capsizing due to broaching, which is crucial for ship A, did not occur with ship B. However, *broaching without capsizing* was often observed for $F_n > 0.43$ and –5 degrees > χ_c > –15 degrees. An example is shown in Fig. 20. Since the largest roll angle due to broaching was about 20 degrees and was almost equal to the roll

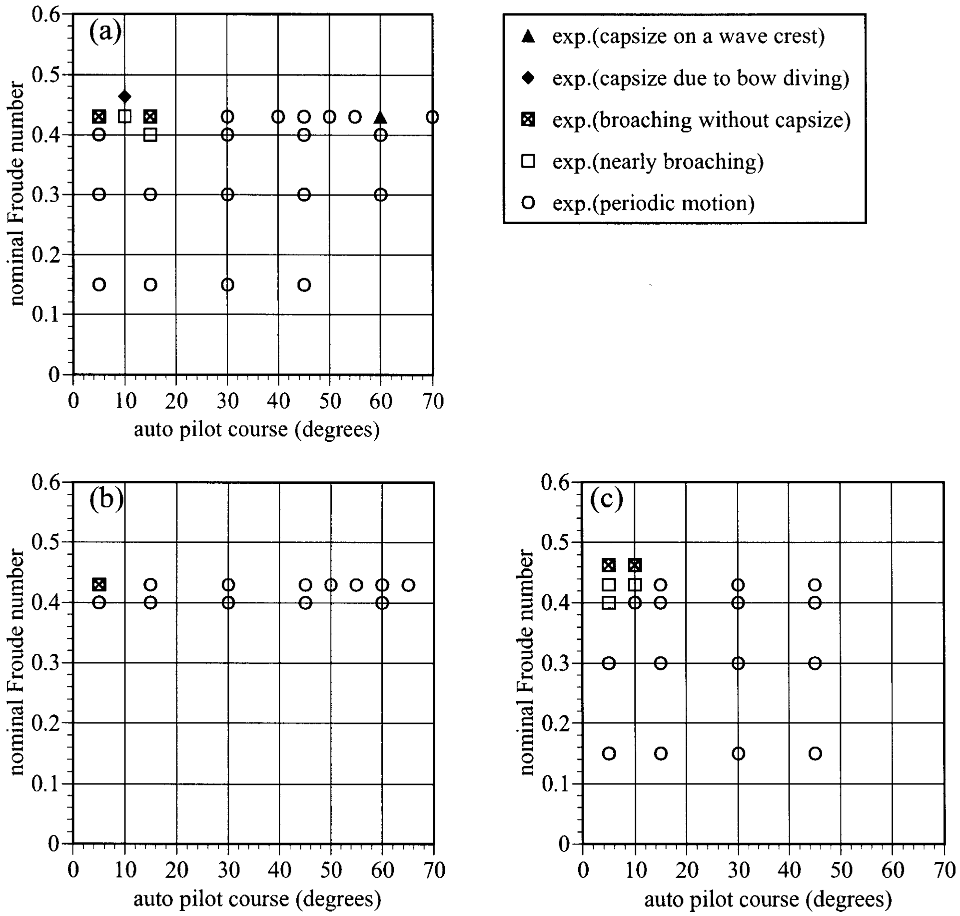

Fig. 16. Results of experiments for ship B running in quartering seas with (**a**) GM = 1.36 m, (**b**) GM = 1.49 m, and (**c**) GM = 1.65 m

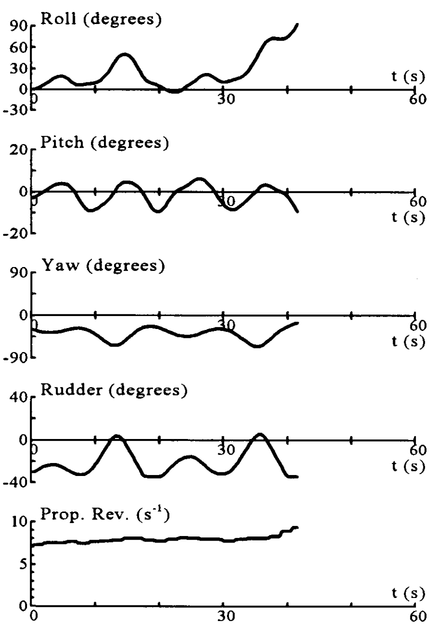

Fig. 17. Time series of capsizing due to stability loss on a wave crest for ship B with GM = 1.36 m, χ_c = –60 degrees, and F_n = 0.43

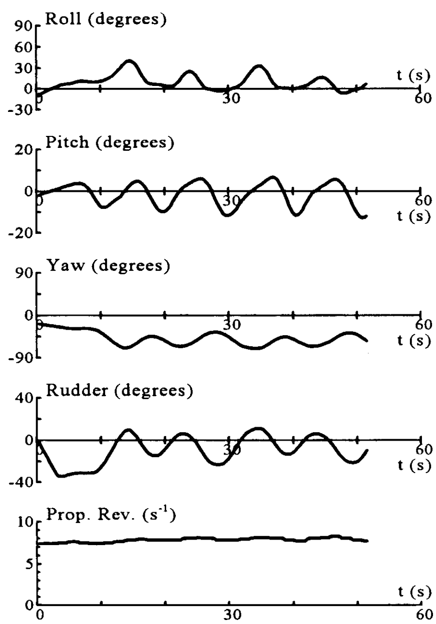

Fig. 18. Time series of a periodic motion for ship B with GM = 1.49 m, λ/L = 1.127, χ_c = –30 degrees, and F_n = 0.43

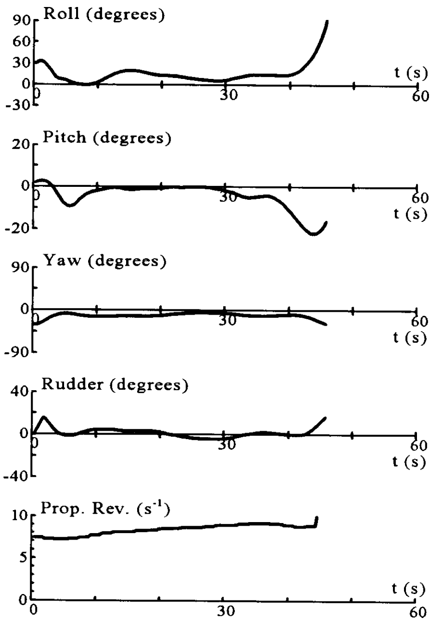

Fig. 19. Time series of capsizing due to bow diving or plow-in for ship B with GM = 1.36 m, $\chi_c = -10$ degrees, and $F_n = 0.46$

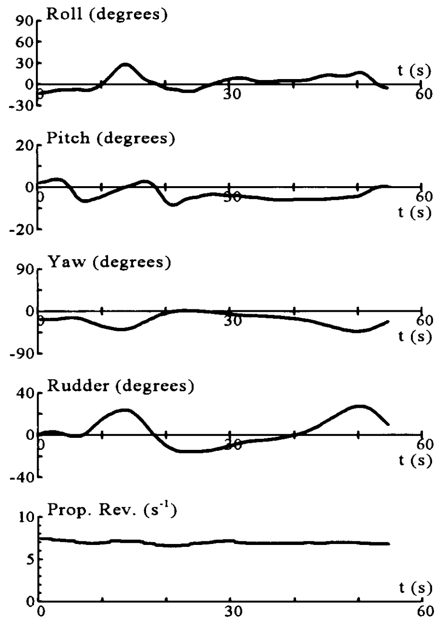

Fig. 21. Time series of nearly broaching for ship B with GM = 1.36 m, $\chi_c = -15$, degrees and $F_n = 0.40$

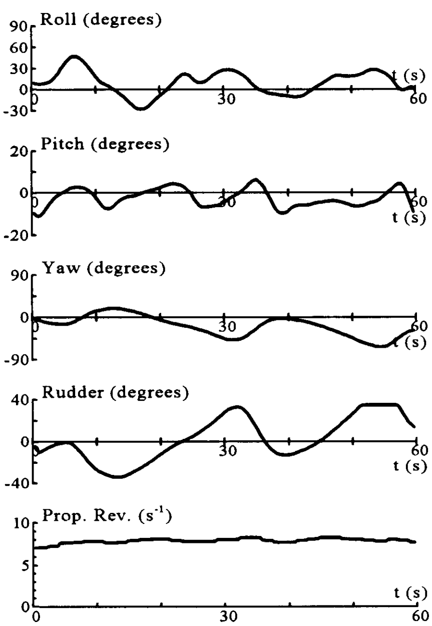

Fig. 20. Time series of broaching for ship B with GM = 1.36 m, $\chi_c = -15$ degrees, and $F_n = 0.43$

angle for the maximum righting lever, this broaching still involves considerable danger of capsizing. If the GM of ship B is slightly reduced, *capsizing due to broaching* might occur. Similarly, there is also a possibility of *capsizing due to loss of stability on a wave crest* for ship A if model runs are carried out to intensively explore the region near $\chi_c = -60$ degrees. Another type of nonperiodic behavior categorized in this paper is *nearly broaching*. An example of this behavior is shown in Fig. 21. The nominal F_n is slightly smaller than in the case shown in Fig. 20. Under surf-riding, the yaw angle increased but the yaw rate was small. Before the rudder angle reached its limit, the model was overtaken by a wave. Here the roll angle was not so large as that during true broaching. Since broaching plays an important role in capsizing and is closely related to steering, the choice of autopilot type and gains is important for capsizing model experiments. Although a simple proportional autopilot was used here, the sensitivity of the autopilot on capsizing should be experimentally investigated in the future.

The region of operational parameters for broaching of ship B, as shown in Fig. 16, enlarged when GM decreased. However, this qualitative relationship between GM and broaching was not confirmed for ship A. In addition, for a warship, Nicholson[25] experimentally found that large GM enlarged the broaching region. Thus, it is difficult to establish a simple relationship between GM and broaching, which might depend on hull form or other details of the ship.

There is no large difference in hull form between ship A and ship B. Strictly speaking, ship A is slightly more slender and has a slightly smaller rudder area ratio, A_R/Ld_m. The nondimensional thresholds, which are obtained by dividing critical GM by the ship's breadth, are 0.164–0.192 and 0.200–0.219, respectively, for ships A and B. This indicates that ship B is slightly more vulnerable to capsizing than ship A, while the IMO IS Code significantly overpredicts the difference between the two. Whether small differences in design parameters can explain the difference in vulnerability is an issue for future researches with captive model experiments and mathematical models.

In view of the fact that for both ship A and ship B, model runs in quartering seas were the worst scenario, it can be stated that experiments in turning, drifting, and head seas may be omitted. However, model runs in quartering waves have to start from a drifting condition for waiting wave propagation and then adjust course with some steering. Thus, it is still important to confirm capsizing conditions in drifting and turning first. If we first try a model run in quartering seas, the model may capsize before speed and course have been adjusted.

In the two examples presented here, the capsizing thresholds are determined with rather limited combinations of wave length, nominal F_n, and autopilot course. Thus, there is a possibility that capsizing can be observed outside these combinations, if the capsizing boundary is very complicated. Although a comparison between experiment and theory[26] suggests that the capsizing boundary obtained by the experiment for such a limited number of combinations can be justified, more theoretical investigations[27] and model experiments with denser grids are expected to establish the qualitative natures of the capsizing boundary.

Conclusions

A rational and efficient method for assessing intact ship stability with free-running model experiments was proposed. The first capsizing thresholds for a model turning in calm water and drifting in the steepest regular waves should be identified. Then capsizing thresholds for model runs in steepest quartering regular waves should be systematically explored. The experimental results based on this method for two purse seiners provided the following conclusions:

1. For a 135GT purse seiner, the capsizing threshold in metacentric height is between 1.25 and 1.46 m, while the IMO IS Code requires 1.00 m. Capsizing due to broaching in quartering seas was observed just above the threshold.
2. For an 80GT purse seiner, the capsizing threshold in metacentric height was between 1.36 and 1.49 m, while the IMO IS Code requires 1.60 m. Capsizing due to loss of stability on a wave crest in quartering seas was observed just above the threshold.
3. *Capsizing due to bow diving or plow-in* was observed when the 80GT purse seiners runs with the nominal F_n 0.46 in quartering seas.
4. No capsizing was observed for a model complying with the IMO IS Code if its operation was based on the recommendation of the IMO guidance in following and quartering seas.

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