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Experimental assessment of critical stability parameters related to wave height

SUMMARY

In the period of 1992÷94 the team of Ship Hydromechanics Division, Technical University of Gdańsk carried out experiments with the free runnig ship model on the lake in various weather conditions. The aim of the model tests was to collect information about ship capsizing related to significant wave height and various stability parameters. The procedure of carrying out the investigations is described. Stability criteria in function of the wave height were established on the basis of the experimental results. Compliance with the proposals is expected to protect the ship against capsizing at sea if the wave conditions are known.

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INTRODUCTION

The crew of the ship as well as ship stability parameters influence her ability of noncapsizing during severe sea conditions. Many stability standards derived from statistical data , mostly connected with righting arm curve, can be found in publications. However very few stability criteria derived from model tests results are known.

It is evident that the wave height has great influence on ship behaviour and safety at sea. The wave development and wave height depend on wind: its direction, speed and time duration . The larger its fetch the larger the wave height. The existing stability criteria derived from statistical data take into account only that some ships with specific stability parameters capsized in heavy weather or on the contrary that some ships did not capsize even during long time of service. The stability standards can be also derived on the basis of theoretical investigations by taking into account all possible oscillatory motions of the ship in waves and also on the basis of model tests. The model tests are usually carried out not very often or in a rather narrow range due to their high costs, mostly to verify a particular case of theoretical calculations. For that reason not many publications with systematic stability model tests can be found.

Due to the lack of information the experiments in open waters at various weather conditions and at various stability parameters of the tested model [1,2] were carried out by Ship Hydromechanics Division, Technical University of Gdańsk some years ago. The results obtained from the experiments made it possible to establish some preliminary recommendations concerning the stability parameters required to protect the ship against capsizing at a given wave condition.

IDEA OF INVESTIGATION

In the recent time, due to many stability accidents with Ro-Ro ferry ships, a trend is observed to take into account the wave height which can occur on a specific area, mostly in calculating damage stability. As the wave height evidently influences ship safety, limited experimental tests were decided to be carried out to describe the conditions at which the capsizing can occur in rough waters. The aim of such tests was to get better knowledge about capsizing conditions and after collection of a sufficient amount of results to try to establish the required stability parameters described by the righting arm curve and related to weather conditions (described by the significant wave height) in which capsizing would not occur. An additional aim was to elaborate an appropriate testing technique, to gain experience in testing to be prepared to continue such experiments in the future [3].

The range of such experiments was limited due to a great number of the involved parameters . The basis of such tests was the free running model with an appropriate speed at any heading angle, the centre of gravity of which could be easily and quickly changed during the tests. At any time the still water righting arm curve could be known. The weather conditions were determined by means of continuous wave height measurements. The tests were limited to recording the event of capsizing or not-capsizing. The model oscillatory motions were neglected.

MODEL

The experiments were carried out with the use of a model of 450 dwt side fishing trawler built in series in Poland in 1951÷61. The model was in storage in a quite good condition, nearly ready to such experiments. It was the only reason of using it. Also its dimensions were suitable for the Jeziorak lake. The model was built of wood and was completely watertight even after capsizing. It was fitted out with propulsive and steering arrangements. During the tests the model was completely free and able to perform all possible motions. All manoeuvres were under remote control. The basic body of the model was fitted out with a bulkwark and superstructure. In some experiments the model depth was increased by covering its open deck with a layer of very light plastic mass up to the top of the bulkwark. In this case the model was tested without the bulkwark and with the lower superstructure only. It was possible to put or remove the additional layer very quickly during experiments.

All ballast weights were carefully fixed. A part of the ballast was attached to a vertical rod on the superstructure deck. Vertical position of the centre of gravity of the model could be easily changed by shifting the deck ballast up or down along the rod. The moment of inertia of the mass could be also changed by shifting the deck ballast in the transverse direction. Main particulars of the model and ship are given in Tab.1.

Tab.1. Main particulars of model and ship

Side trawler - 1:25 model scale			
Main particulars		Model	Ship
Length overall	L_{OA}[m]	2.369	59.23
Length between perpendiculars	L_{BP}[m]	2.140	53.50
Breadth	B[m]	0.360	9.00
Basic body			
Depth	D[m]	0.198	4.95
Draught	d[m]	0.174	4.34
Displacement	V[m^3]	0.0785	1227
Model with the increased depth			
Depth	D[m]	0.238	5.95
Draught	d[m]	0.176	4.40
Displacement	V[m^3]	0.0799	1248

Some experiments with a model of the cargo ship HEL [4] were also carried out apart from the experiments with the side trawler. The model was much larger than the previous one: L_{BP} = 3.40 m, B = 0.518 m, V = 0.190 m^3. The tests were carried out nearby the Sopot pier, in the Bay of Gdańsk.. The model which complied with the IMO Res.A.167 recommendations did not show any tendency to capsizing at given weather conditions.

TECHNIQUE OF EXPERIMENT

The righting arm curve within the full range of heel angles and the initial metacentric height at a specific position of the deck ballast were estimated in the laboratory. During tests on the lake the deck ballast was shifted to a carefully measured distance so the stability parameters were known at each run of the model. The waves were recorded by a gauge attached to a float consisting of three vertical pipes. A horizontal plate situated in lower part of the float limited its heave motion. A processor in watertight box was fixed on the top of the float above water level. The gauge and processor were under remote control. The water level was recorded at each of 0.05 s period during 15 minutes. After that time the next recording cycle could start. In this way each run of the model had its respective wave record from which the significant wave height was calculated. The float was attached, to avoid the heel, through a line to a small buoy anchored to the lake bottom in a chosen position (see Fig.1).

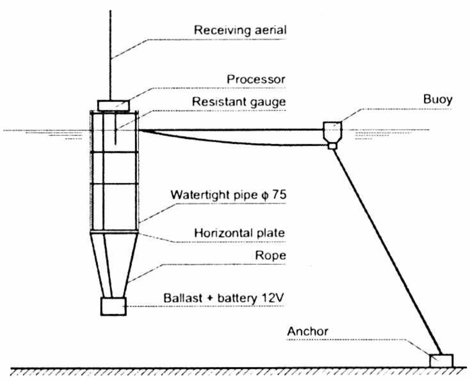

Fig.1. Wave recorder

The float was kept in the upright position by the ballast hanging on three ropes. 12 V battery supplying the gauge and processor was also installed besides the steel ballast in the watertight box deep in the water. The total mass of the wave recording arrangement was 60 kg. The model was operated around the wave gauge in the distance up to 150 m. The test always started from the lowest position of the deck ballast. At first the model was run with the power equivalent to service speed in head waves (180°course angle), then oblique waves (135°), and beam waves (90°). For some time the engine was stopped and the model was freely drifting during a few minutes. Afterwards the model was run in quartering waves (45°) and at last in following waves (0°). Such test was repeated many times. When the model did not capsize the deck ballast was shifted up and the test was continued until capsizing the model. The investigations were repeated at different weather conditions.

MODEL TEST RESULTS

The tests were carried out, as far as the full scale is considered, in the range of the significant wave height $h_{1/3}$=1.60÷3,75 m and the relative wave height $\frac{h_{1/3}}{L_{BP}} \cdot 100 = 2.99÷7.01$.

The experimental results were presented on the diagrams with various stability parameters plotted against the significant wave height [5]. Fig.2 is an example of the model test results elaborated for one stability parameter. It can be seen that if the model capsized the limiting line between safe and dangerous zone could be established. Seven parameters were considered.

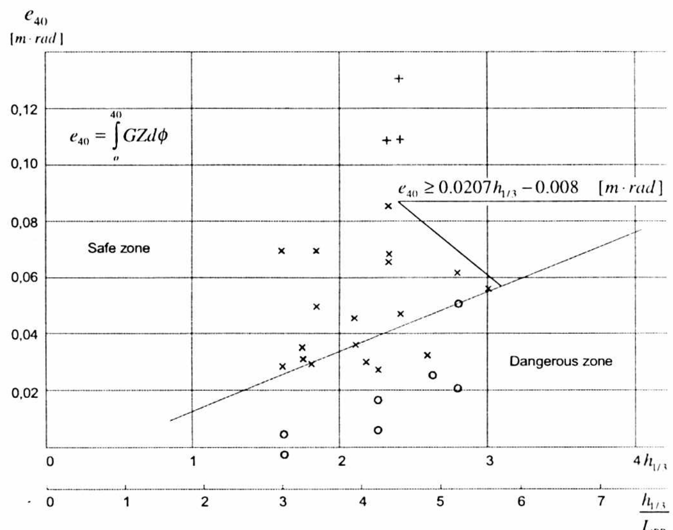

Fig.2. The required area below the righting arm curve, counted up to 40 heel angle versus the relative wave height

Notation:
+ Model complies with IMO Res.A.168 and does not capsize
× Model does not comply with IMO Res.A.168 and does not capsize
o Model does not comply with IMO Res.A.168 and capsizes

The processed results valid for the significant wave height of 1.60÷3.75 m are as follows :

1. The coefficient of initial stability :

$$\frac{GM \cdot F_b}{B} \geq 0.006\, h_{1/3} + 0.008 \quad [m] \qquad (1)$$

where F_b = (D - d) is the freeboard.

2. The righting arm at 30° heel angle :

$$GZ_{30} \geq 0.0355\, h_{1/3} - 0.026 \quad [m] \qquad (2)$$

3. The righting arm at 40° heel angle :

$$GZ_{40} \geq 0.0545\, h_{1/3} - 0.080 \quad [m] \qquad (3)$$

4. The area below the righting arm curve, counted up to 30° heel angle :

$$e_{30} \geq 0.0158\, h_{1/3} - 0.005 \quad [m \cdot rad] \qquad (4)$$

5. The area below the righting arm curve, counted up to 40° heel angle :

$$e_{40} \geq 0.0207\, h_{1/3} - 0.008 \quad [m \cdot rad] \qquad (5)$$

6. The area below the righting arm curve, counted up to 60° heel angle :

$$e_{60} \geq 0.0427\, h_{1/3} - 0.010 \quad [m \cdot rad] \qquad (6)$$

7. The first moment of the area below the righting arm curve, counted up to 60° heel angle :

$$M_{60} \geq 0.032\, h_{1/3} - 0.014 \quad [m \cdot rad^2] \qquad (7)$$

EXTENDED ASSESSMENT OF WAVE HEIGHT EFFECT ON THE REQUIRED STABILITY PARAMETERS

Rather low value of the significant wave height was a great disadvantage of the model tests. This disadvantage could be partially removed by adopting another experimental results. The systematic model tests were used in the approximate method of righting arm calculation for the ship placed on wave crest and trough, elaborated by J.I.Nieczajew in [6]. For the trawler in question the range of the significant wave height can be extended with the aid of the method to 6 m and the relative wave height to 11. The loss of righting arm for the ship on wave crest for several wave heights was calculated by means of the method. The righting arm was assumed not to be smaller than the calculated losses. The new criteria valid to wave heights up to 6 m was obtained by taking into account the experimental and calculated results. The processed results are as follows :

1. $$\frac{GM \cdot F_b}{B} \geq 0.003 + 0.013\, h_{1/3} \quad [m] \qquad (8)$$

2. $$GZ_{30} \geq 0.0800\, h_{1/3}^{0.522} \quad [m] \qquad (9)$$

3. $$GZ_{40} \geq 0.0700\, h_{1/3}^{0.518} \quad [m] \qquad (10)$$

4. $$e_{30} \geq 0.0225\, h_{1/3}^{0.539} \quad [m \cdot rad] \qquad (11)$$

5. $$e_{40} \geq 0.0285\, h_{1/3}^{0.670} \quad [m \cdot rad] \qquad (12)$$

6. $$e_{60} \geq 0.0562\, h_{1/3}^{0.645} \quad [m \cdot rad] \qquad (13)$$

7. $$M_{60} \geq 0.379\, h_{1/3}^{0.622} \quad [m \cdot rad^2] \qquad (14)$$

GENERAL COMMENTS

The second basic disadvantage of the investigations is that only one model was tested. It can be said however that two models were tested because the depth of the model was alternatively increased. The presented recommendations can be also compared with the model test results of the cargo ship HEL. The results are in general agreement with the above submitted formulas. Only the initial stability coefficients differ. For ships with higher freeboard, e.g. D/d ≈ 1.4, the coefficient value can be smaller than that recommended.

The stability proposals can also be compared with the recommendations for container ships, given in the Code on Intact Stability [7] which was also derived from model tests. The IMO criteria elaborated by Hamburg Towing Tank applied to the ship HEL are in compliance with the given formulas extrapolated to the significant wave height of 10 m. However the recommendations for container ships applied to the fishing trawler in question lead to the following conclusions :

- the criteria [7] are more stringent than the criteria of IMO Res.A.168
- the ship with higher freeboard may have lower values of the righting arm curve
- values of the stability pameters according to [7] calculated for the ship with high freeboard, D/d ≈ 1.35, are in agreement with the above proposed formulas for the significant wave height of about 6 m
- such values calculated for the ship with low freeboard, D/d ≈ 1.13, are in agreement with the submitted formulas for the significant wave height of about 10 m.

PROPOSAL OF STABILITY STANDARDS

A trend is observed to elaborate new stability standards by applying an advanced approach to ship behaviour in rough seas, e.g. the idea of adopting the probabilistic concept to intact stability calculations, given several years ago. However many general proposals and no applicable solutions have been submitted till now. It seems therefore that the fundamental assessment of ship stability based on the still water righting arm curve, introduced to ship practice in the last century, will be utilized also in the nearest future.

It is clear that ship's stability can be improved by increasing :

- freeboard
- flooding angle
- some stability parameters.

According to IMO document [8] ships are to be considered within two separate categories:

- A ship : ship with additional form stability for which the righting arm curve is above the tangent at its origin
- B ship : ship without additional form stability for which the righting arm curve is below the tangent at its origin.

The proposal is also given [8] that the dynamic righting arm at 30° and 40° heel angles as well as the initial metacentric height should be grater than those provided in IMO Resolution A.167 and A.168, and the values should be even greater for B ships than A ships.

A procedure for practical stability calculations should be quick and simple and number of involved parameters should be as low as possible. Sometimes it can be useful to relate stability standards to the wave height. In this way the standards could be less stringent for some water regions and more stringent for others.

In general the flooding angle should be of a high value e.g.:

$$\phi_F \geq 50° \qquad (15)$$

which is connected with an appropriate freeboard value.

The position of the maximum value of the righting arm curve, which should be at least at 30° heel angle, is also an important stability parameter so that :

$$GZ_{\max} \quad \text{at} \quad \phi_m \geq 30° \qquad (16)$$

The following relationships are proposed taking into account the above mentioned results and recommendations:

➲ the initial metacentric height :

for A ships

$$GM \geq 0.125\, h_{1/3}^{0.547} \quad [m] \qquad (17)$$

and for B ships

$$GM \geq 0.206\, h_{1/3}^{0.547} \quad [m] \qquad (18)$$

➲ the righting arm at 30° heel angle :

$$GZ_{30} \geq 0.080\, h_{1/3}^{0.522} \quad [m] \qquad (19)$$

➲ the area below the righting arm curve, counted up to :

30° heel angle :

$$e_{30} \geq 0.0225\, h_{1/3}^{0.539} \quad [m \cdot rad] \qquad (20)$$

40° heel angle :

$$e_{40} \geq 0.0285\, h_{1/3}^{0.670} \quad [m \cdot rad] \qquad (21)$$

FINAL REMARKS

It is necessary to verify the above given proposals by extending the stability tests to different ship models in various load conditions, to be performed in open waters and higher waves. Their results would be also interesting from the theoretical point of view.

NOMENCLATURE

B	-	breadth of the hull
D	-	depth
d	-	draught
$e_{30,40,60}$	-	area below the righting arm curve up to respective angle of heel
F_b	-	freeboard
GM	-	initial metacentric height
$GZ_{30,40}$	-	righting arm at respective angle of heel
$h_{1/3}$	-	significant wave height
L_{BP}	-	length between perpendiculars
L_{OA}	-	overall length
M_{60}	-	first moment of the area below the righting arm curve up to 60°
V	-	displacement
ϕ	-	heel angle
ϕ_F	-	flooding angle
ϕ_m	-	the heel angle at which the righting arm curve achieves its maximum value

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Appraised by Wiesław Wełnicki, Assist.Prof.,D.Sc.,N.A.

Conferences

Drive and Steering Systems '98

From 18 to 20 February 1998 IV Fair of Drive and Steering Systems gathering together producers, co-producers and suppliers of the systems was held in Gdańsk. Technical University of Gdańsk took patronate of the Fair and arranged a seminar accompanying it. The seminar gave an occasion to producers and operators of the systems to demonstrate their design and research achievements. It was realized by presenting 31 papers and 6 development offers. The papers were split into two topic groups :

- ❑ Electronic and computerized steering systems (10 papers)
- ❑ Machine drives and steering systems (21 papers)

The papers dealing directly with shipbuilding were presented within the second topic group and covered the following themes :

- „Design concept classification of the main ship propulsion systems and electric power plants specific for a given ship type" (by J.Jamroż, T. Wieszczeczyński, Ocean Engineering and Ship Technology Faculty)
- „Dynamics of a ship propulsion system with shaft generator. Comparative analysis of simulative and experimental investigations" (by W. Próchnicki, Ocean Engineering and Ship Technology Faculty)
- „The energy saving short range fishing vessels, KR 10÷12" (by J.Krępa, Ocean Engineering and Ship Technology Faculty)
- „Dynamic modelling of the propulsion and steering systems" (by E. Wittbrodt, Mechanical Faculty)
- „Steering system and vectorial propulsion system of the cable hoisting winch for underwater vehicles" (by L. Rowiński, Ocean Engineering and Ship Technology Faculty)
- „Propulsion plants for ships navigating in waters with ice conditions" (by A. Balcerski, Mechanical Faculty, D. Bocheński, Ocean Engineering and Ship Technology Faculty)
- „Propulsion plants for the dredgers with a system of hydraulic hoisting and carrying away of spoil" (by D. Bocheński, Ocean Engineering and Ship Technology Faculty, and A. Balcerski, Mechanical Faculty).

ERRATA

The correct form of the formula (8) given in the paper titled **„On selecting the control-measuring instruments for ship power plants in compliance with the requirements of classification societes"** by J. Mindykowski, D. Pajórek and H. Pepliński, published in the Polish Maritime Research no 1/98, is as follows :

$$\delta Y = \delta Y_m + \delta Y_a = \sum_{1}^{n} \delta q_i + \frac{\sum_{n+1}^{n+k} q_i \cdot \delta q_i}{\sum_{n+1}^{n+k} q_i}$$

The Editor apologizes for the occurred error.