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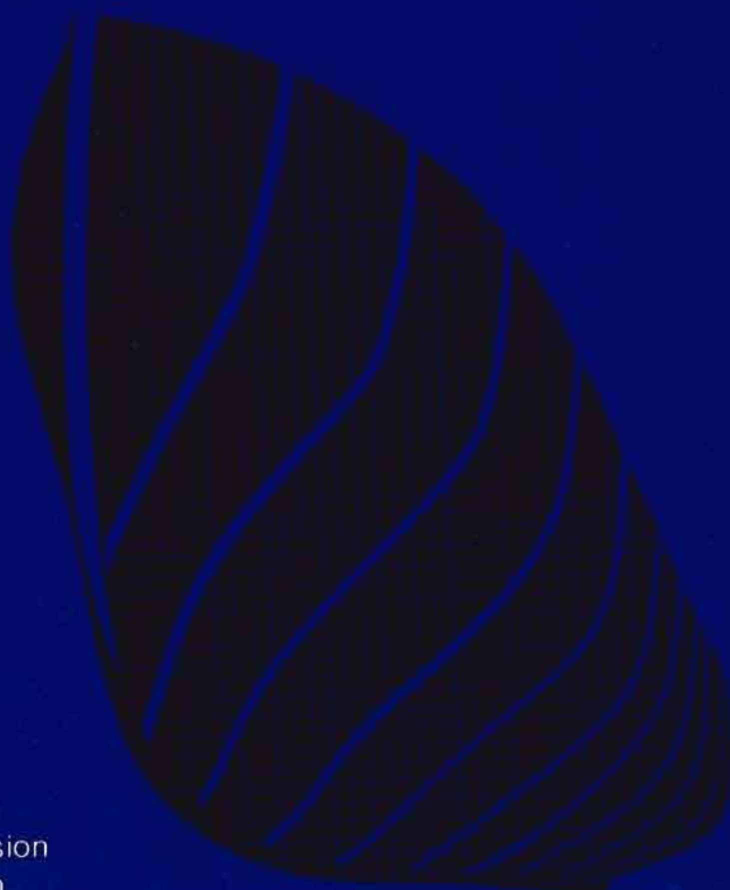
AN ASSESSMENT OF STABILITY CRITERIA FOR SMALL SURFACE SHIPS



Vessels and Engineering Division
Industrial Development Branch

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AN ASSESSMENT OF STABILITY CRITERIA FOR SMALL SURFACE SHIPS

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Opinions expressed and conclusions reached by the author are not necessarily endorsed by the sponsors of this project

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authority of the
Honourable Jack Davis, P.C., M.P.,
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Environment Canada

AUTHORITY

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OBJECTIVE

(a) To assist in the development of stability criteria for decked fishing vessels under 80 feet in length.

(b) To assess present criteria for larger vessels, i.e. M.O.T., I.M.C.O. and other available standards.

(c) To assess available data for both successful and unsuccessful vessels.

SUMMARY

An empirical method for estimating the loss of stability when a vessel is travelling in a following sea was investigated. The findings were compared with experimental values. The method was then used to predict the loss of stability of a small Canadian fishing vessel. In addition, several stability criteria were examined with a view to assessing their appropriateness for fishing vessel design.

THE STABILITY PROBLEM

One of the great naval architects of his time, A. N. Krylov, presented a paper to the Institution of Naval Architects in 1898 in which he promised to solve the problem of transverse stability in a seaway. Seventy-five years have now passed and this elusive goal has not yet been achieved.

Capsizing of vessels occurs more often than is generally recognized. The majority of these are less than 150 feet in length. Wear and tear have no appreciable effect as the vessels are often in service for less than three years.

STABILITY IN A FOLLOWING SEA

Many cases are cited of the loss of fishing vessels while travelling in a following sea. A study was undertaken to determine whether the empirical formula developed by Nechayev (reference 1) was suitable for predicting the loss of righting lever under these conditions. The calculated result was compared with the experimental findings of Beukelman and Versluis (reference 2). The calculations are given in Appendix A and the comparison is shown in Figure 1.

Experiments using modified versions of the parent ship were also described in reference 2. Agreement with Nechayev's method was good in all cases except for the model with a low prismatic coefficient. In that case the calculated prediction was more severe than the experimental value.

The magnitude of the reduction will vary appreciably from ship to ship since it is a function of the vessel's main dimensions and form coefficients. Examples have been cited where the loss due to this effect was as much as 50 per cent of the steady state righting lever (reference 3).

The calculated reduction for the fishing vessel Marc Guylaine II is given in Appendix B. These results are compared with the intact stability calculated in reference 4. The comparison is shown in Figure 2.

PREDICTION OF STABILITY USING SIMPLE CONVENIENT DIMENSIONS

A search for a simplified method of presenting a vessel's stability is unlikely to prove fruitful. Several methods have been put forward and nearly all of these are directly or indirectly dependent on the initial metacentric height. One such method proposed by Takagi (reference 5) was examined and found unsatisfactory as ships which were lost met the proposed criteria. This method was based on GM, BG, freeboard and beam.

Mok and Hill (reference 6) shows that initial metacentric height can be very misleading when considering a ship's stability. In the case of the supply vessels described in their paper the initial metacentric height was so great it appeared that the ships could have no stability problem. The truth of the matter was that many of them capsized over a short period of time. Any method which does not take into account the changed characteristics of the steady state stability curve under dynamic conditions is doomed to failure.

PREDICTION OF STABILITY BY A COMPARISON OF HEELING MOMENTS AND RIGHTING MOMENTS

There is a school of thought that the ideal method to use in predicting stability is the use of heeling moments. A paper summarizing these and a method for determining their magnitude is given by K. Wendal (reference 7). He argues that sufficient stability can only be ensured by balancing righting and heeling moments. While no objection can be taken against this argument the method is unlikely to be successful. In the first place one must be certain that all the heeling effects are taken into account and secondly that their magnitudes are accurately assessed. The transient losses that take place in the righting moments must be added as heeling moments.

For example, the loss of righting lever due to a following sea must be included as a heeling lever. In addition there are are cross coupling effects, as for example that between yaw, pitch and roll, whose presence and effects are obscure or unknown.

PREDICTION OF STABILITY BY STATISTICAL METHODS

It appears that the best method for predicting the stability of small vessels lies in a statistical approach. The underlying principle is that a large number of unsuccessful as well as successful vessels are analyzed and an empirical method found which will exclude the casualties. Several criteria based on this idea exist and will be discussed later in the paper.

It has been argued that empirical data derived from statistics of casualties are only useful for similar ships operating under similar conditions. It will be shown, however, that one such criteria proposed by Rahola (reference 8) holds for different types of small vessels over a range of operating conditions.

U.S.N. STABILITY CRITERIA

The stability criteria which is followed by the United States Navy is described in reference 9. The same criteria has been adopted by the Royal Canadian Navy and is given in reference 10.

The procedure in the U.S.N. is to design the ship to withstand the maximum amount of damage with due consideration given to the size and military importance of the particular ship. The criteria developed as a result of war damage experience, model and full scale explosion tests and operating experience. Once these design objectives are fulfilled the ship's stability is checked against beam winds combined with rolling in a rough sea, lifting of heavy weights over the side, high speed turning and top side icing. Generally speaking once the damaged criteria is met the intact stability will be satisfactory.

A strong case can be made for the design of a fishing vessel by a similar method. The normal mode of operation of a fishing vessel is such that flooding of the deck, the free surface effect due to entrapped water and the loss of waterplane area ia a continual occurrence analagous to a ship operating in a damaged condition. Unlike their counterparts, however, little design information is available on the magnitudes of these effects.

RAHOLA'S STABILITY CRITERIA

Rahola's method is based on the statistical study of a number of small vessels. His paper was published in 1939. Although the original paper was not available, excerpts summarizing the criteria are given in references 6 and 11. The requirements are:

(a) The righting lever at 20 degrees heel must be at least 5 1/2 inches (14 cm).

(b) The righting lever at 30 degrees heel must be at least 7 7/9 inches (20 cm).

(c) The area under the righting arm must equal 15 ft-degrees up to the least of the following angles:

(i) 40 degrees
(ii) angle corresponding to maximum righting arm
(iii) angle at which openings immerse (down flooding)

Several countries including the Netherlands adopted Rahola's standard. Dewit (reference 11) states that in the cases that had come to the attention of the Netherlands Shipping Inspection Service it was found that Rahola's criteria was reliable for judging the stability of a fishing vessel. His paper was illustrated with a number of successful and unsuccessful vessels. Those that proved unsatisfactory failed to meet Rahola's standard.

In his comments on reference 5, Rahola stated that one ought to be very careful about the judging of stability if the regulations in force were not at least as severe as his dynamical method. In reference to the difficulty of meeting his criteria in the design of fishing vessels he pointed out that his method was not as severe as that adopted by the Russians in their 1947 Regulations and that although these were revised in 1956 they were still stricter than his. He pointed out that Finnish designers had difficulty in meeting the Russian standards whereas his criteria gave them no such problem.

IMCO'S STABILITY CRITERIA

IMCO's criteria was developed from statistics in a similar manner to Rahola's. The method used in arriving at the standard is outlined in reference 12 and the requirements are given in reference 13. The requirements are:

(a) The area under the righting lever curve should not be less than .055 metre-radians (10.4 ft-degrees) up to the 30 degree angle of heel and not less than .09 metre-radians (16.9 ft-degrees) up to 40 degree angle of heel or the angle of flooding if this angle is less than 40 degrees.

Additionally the area under the curve between the angles of heel of 30 degrees and 40 degrees (or the angle of flooding) should not be less than .03 metre-radians (5.6 ft-degrees).

(b) The maximum righting lever should be at least 20 cm (7 7/9 inches) at an angle of heel greater than or equal to 30 degrees.

(c) The maximum righting arm should occur at an angle of heel preferably exceeding 30 degrees but not less than 25 degrees.

(d) The initial metacentric height should not be less than .35 meters (1.15 ft).

COMPARISON OF RAHOLA'S AND IMCO'S CRITERIA

The main difference between the two criteria is that IMCO permits the maximum righting lever to occur at a low angle of heel (25 degrees) without any dynamical requirement at that point. Rahola would also permit the maximum lever to occur at 25 degrees (or lower) provided that the dynamical righting lever is 15 ft-degrees. Such a situation would require a large initial metacentric height. While satisfactory for certain classes of vessels, this would be unsatisfactory for fishing vessels. In general, conventional fishing vessels which have their maximum righting levers at low angles of heel will be unable to meet Rahola's standard.

One of the figures taken from Dewit's paper is reproduced as Figure 6. This curve meets IMCO's criteria but falls short of Rahola's. The maximum righting lever occurs at 26 degrees and the dynamical lever is approximately 13 ft-degrees. According to Dewit this 105 foot vessel proved unsatisfactory in service.

Marc Guylaine II, Figure 3, marginally meets IMCO's criteria but the dynamical lever up to the angle of maximum righting lever (25 degrees) is approximately 11 ft-degrees. This is almost 30 per cent less than Rahola's required value.

Figure 5 shows the stability curve for a fishing vessel which was lost. The characteristics are taken from reference 12. For comparison the curve for Marc Guylaine II has been superimposed on the figure. It will be observed that there is little difference between the stability characteristics of the two vessels. In the worst condition the curve marginally meets IMCO's criteria but fails Rahola's by a large margin.

A paper by Mok and Hill (reference 6) outlines the stability problems associated with supply vessels which serviced off shore drilling rigs. These vessels of varying shapes and dimensions had one thing in common, a serious stability problem. A study of the stability problem led to a "discovery" of Rahola. Since this criteria was applied to these vessels no losses attributed to lack of stability have arisen.

Figure 4 has been reproduced from the above paper and shows the stability curve of a typical successful supply vessel and one for the "Borie", a vessel which capsized in service. The "Borie" fails to meet Rahola's criteria because of insufficient dynamical lever and IMCO's because the maximum righting lever occurs below 25 degrees heel. The successful supply vessel meets Rahola's but fails to meet IMCO's. Strictly speaking, IMCO's criteria was developed specifically for fishing vessels. This figure, however, shows that Rahola's criteria is versatile meeting requirements of different types of small vessels operating in a different environment.

RAHOLA'S CRITERIA RECOMMENDED

From the cases which were available for examination Rahola's criteria proved superior to that recommended by IMCO.

Prior to assessing Rahola's standard the writer had envisaged an effect due to loss of righting arm under dynamic conditions of 0.5 feet at an angle of heel of 40 degrees. A line was then drawn from the origin to the 40 degree angle as shown in Figure 7. The remaining area under the stability curve was designated the "effective area". The reason for this modification was the result of the study of loss of righting arm due to a following sea and its probable maximum value. A check of the "effective area" showed that it agreed with the value of the dynamical lever as calculated by Rahola. This was checked for the three vessels shown in Figures 3, 5 and 6, and agreed in each case. It was thus felt that Rahola's criteria includes a sufficient margin for the effect of "transient responses" which modify the stability curve under dynamic conditions.

During 1964-1965 the French merchant marine investigated the loss of two trawlers (reference 14). Two successful vessels were also included in the study. Two important observations resulted from the investigation. The first was that the two vessels which were lost had their maximum righting arms at 26 degrees and 28 degrees respectively whereas the two successful ones peaked at 31 degrees and 36 degrees. Although the stability curves were unavailable for inspection it is unlikely that the casualties met Rahola's criteria especially since their initial metacentric heights were normal for that type of vessel.

The second observation was of importance when considering the design implications of Rahola's standard. The authors showed what must be accomplished in order to extend the maximum righting lever to a larger angle of heel. Briefly they concluded that this extension of the righting lever can be achieved in two ways

(a) by increasing the midship section coefficient

(b) by increasing the freeboard.

Although this needs further analysis it appears that the above offers a solution to those who have encountered difficulty in fulfilling Rahola's requirements. Additional amplification of their work is provided in references 15 and 16.

IMPORTANCE OF ADOPTING A STABILITY CRITERIA

The argument is often put forward that many vessels are successfully operating in spite of the fact that they do not meet suggested standards. There are two reasons why this is the case. In the first place, the loss of righting arm due to a following sea is not as severe in certain vessels as in others depending as it does upon ratios of ship's dimensions and form coefficients. This loss is certainly one of the most severe of the "transient responses" and any reduction in this will separate one vessel from another. In addition a vessel may be no more stable than another and is successful only because it has not encountered the combination of conditions which turned the other into a casualty.

It has been shown, however, that those countries which have adopted a stability standard for fishing vessels have less casualties that those which have not.

COMMENTS ON STABILITY OF MARC GUYLAINE II

At the commencement of this study the characteristics of the Canadian fishing vessel Marc Guylaine II were provided. Two sister ships were lost at sea due to capsizing. Figure 2 shows that the loss of righting lever due to a following sea is rather severe in this vessel. After allowing for this loss the maximum righting arm remaining is a meek 0.5 feet. With this low value the ship would have difficulty in withstanding heeling forces such as those presented when turning at high speed or encountered from other external forces. The vessel fails to meet Rahola's requirements by a large margin and hence must be considered critical. Any attempts to make the vessel seaworthy by the addition of ballast or lengthening the vessel should be checked in light of Rahola's criteria.

FUTURE MODIFICATIONS AND AMPLIFICATION OF RAHOLA'S CRITERIA

Since Rahola's idea was first formulated in 1939 a large number of fishing vessel casualties have occurred. Details of those definitely attributed to loss of stability should be obtained and examined to see whether or not the standard needs adjustment.

There is also the question of how much icing to include when checking a vessel's stability by means of statistical criteria. Since the method has already taken into account the combination of severe transient responses it is unlikely that icing should be added in its entirety. It would appear that the most serious condition would be the statistical criteria plus the amount of icing encountered in a following sea.

A second approach to icing might be to include maximum icing but in that condition to lower the requirement of 15 ft-degrees of dynamical lever. Figure 8 is taken from reference 17 and shows the worst operating condition for the fishing vessel Judy & Linda IV. The vessel readily meets Rahola's criteria in the non-iced condition but in the fully iced condition the dynamical lever becomes approximately 12 ft-degrees. Since this vessel has been operating successfully such a dynamical lever in the iced condition may be sufficient. This question needs further study and it would be of vital importance to have Rahola's original work to see just what conditions and types of vessels were included in his study. In addition, particulars of vessels which were lost due to icing should be obtained.

SHIPMENT OF GREEN WATER

It would be unsound to conclude that the adoption of Rahola's or any other criteria would completely solve the stability problems of fishing vessels. It would, however, eliminate these problems under ordinary operating conditions.

The serious problem of water on the deck is analagous to the U.S.N. design of naval ships under damaged conditions. Even in the above system there comes a time when the damage would be so severe that no amount of intact stability would save the vessel. Likewise in a fishing vessel if the shipment of water reaches the stage where the water is not evacuated before the ship is hit by succeeding waves loss of the vessel could result.

The vessel whose stability characteristics are shown in Figure 5 met both Rahola's and IMCO's criteria at the time of her loss. It was stated, however, that she had shipped water on the deck at that time. Such a condition would lower the satisfactory stability curve to or beyond the worst operating condition. The vessel would then capsize because she no longer met Rahola's criteria. The major difference between the stability characteristics of larger and smaller vessels is the fact that the latter is vulnerable to the shipment of water. The story is recounted where thirteen French vessels were lost in a single night during a terrific storm off the Coast of Brittany. It is unlikely that any amount of initial stability would have saved these vessels.

This problem needs to be studied in depth with emphasis on experimental as well as operational experience. More use should be made of model testing facilities such as those at National Research Council, Ottawa, or National Physical Laboratory, England. Hopefully such tests would indicate the amount of freeboard and sheer a particular vessel should have in order to prevent or at least delay the shipment of large quantities of green water.

CONCLUSIONS AND RECOMMENDATIONS

1. Nechayev's empirical method of determining the righting lever loss due to a following sea is a suitable method for determining its magnitude.

2. A search for a simplified method of presenting a vessel's stability without reference to its righting moment curve is an unlikely possibility.

3. A statistical method is the best approach to the development of stability criteria for small surface ships.

4. Rahola's criteria should be adopted for new fishing vessel design as it would eliminate stability problems of vessels under normal operating conditions. Statistical data should be obtained for recent casualties especially those due to icing to determine whether any adjustment to Rahola's criteria is necessary.

5. The stability of large and small fishing vessels should be judged by the same criteria. The difference in operational performance is due to the greater risk of shipping green water in the case of the smaller vessels. In order to alleviate this problem, model testing should be undertaken which would indicate a suitable freeboard and sheer.

6. IMCO's criteria is unsuitable for assessing the stability of small fishing vessels because it permits the maximum righting lever to occur at too small a heeling angle without a compensation in dynamical lever.

7. The Russian Regulations of 1947 (revised in 1956) should be obtained if possible and their requirements and feasibility assessed.

8. The midship section coefficient and the freeboard play the major part in extending the maximum righting lever to a suitable angle of heel which would permit a vessel's designer to meet Rahola's criteria.

9. When checked against Rahola's standard the fishing vessel Marc Guylaine II has insufficient stability. Any modifications to this vessel should be checked in light of this criteria.

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$$A_6 = .692 - \frac{\delta}{\beta}$$

$$A_7 = Fr - .28$$

ρ, k_1, k_2, k_3, m, n, f are experimental values given in reference 1.

<u>Particulars of Dutch Trawler 1JM 44</u> (reference 2)

L = 23.15 m	B/L = .276
B = 6.40 m	d/B = .358
D = 3.10 m	δ/α = .600
d = 2.29 m	δ/β = .645
δ = .48	Fr = .34
β = .744	d/D = .739
α = .80 (assumed value)	

The wave height used in the Dutch experiments (reference 2) is hw = $\lambda/30$.

$$A_1 = 1/30 = .0333$$

$$A_2 = .208 - .276 = -.068$$

$$A_3 = .375 - .358 = .017$$

$$A_4 = .739 - .770 = -.031$$

$$A_5 = .700 - .600 = .100$$

$$A_6 = .692 - .645 = .047$$

$$A_7 = .34 - .28 = .06$$

APPENDIX A

CALCULATION OF A SHIP'S STABILITY ON A WAVE CREST IN A FOLLOWING SEA

NOTATION

λ = length of wave

h_w = height of wave (from trough to crest)

L = ship's length at the waterline

d = draught amidships

D = depth amidships

δ = block coefficient

α = waterplane area coefficient

β = midship section coefficient

Fr = Froude number

B = breadth of vessel

The reduction GZ (ΔGZ) due to the crest of a wave amidships is given in reference 1. The formula, with notation changed for convenience, becomes:

$$\frac{\Delta GZ}{B} = A_1\rho + A_2k_1 + A_3k_2 + A_4k_3 + A_5m + A_6n + A_7f$$

where $A_1 = \frac{hw}{\lambda}$

$A_2 = .208 - B/L$

$A_3 = .375 - d/B$

$A_4 = d/D - .770$

$A_5 = .700 - \frac{\delta}{\alpha}$

	10°	20°	30°	40°
$A_1\rho$	-.00280	-.00587	-.01030	-.01370
A_2k_1	.00170	.00476	.00850	.01020
A_3k_2	-.00022	-.00041	-.00060	-.00071
A_4k_3	.00047	.00071	.00115	.00140
A_5m	-.00200	-.00300	-.00400	-.00480
A_6n	-.00127	-.00212	-.00235	-.00259
A_7f	-.00036	-.00090	-.00156	-.00198
$\frac{\Delta GZ}{B}$	-.00448	-.00683	-.00916	-.01218
ΔGZ	-2.9 cm	-4.4 cm	-5.9 cm	-7.8 cm

A comparison of the predicted values using the empirical method versus experimental values is shown in Figure 1.

PREDICTION OF LOSS OF RIGHTING ARM LEVERS FOR MARC GUYLAINE II WHEN IN A FOLLOWING SEA

Particulars of Marc Guylaine II as inclined (Reference 4)

$L = 22.3$ m	$B/L = .300$
$B = 6.7$ m	$d/B = .330$
$D = 3.4$ m	$\delta/\alpha = .550$
$d = 2.21$ m	$\delta/\beta = .62$
$\delta = .44$	$Fr = .34$
$\beta = .71$	$d/D = .65$
$\alpha = .80$	

The wave height used in the calculation is $h_w = \lambda/20$.

$A_1 = 1/20 = .050$

$A_2 = .208 - .300 = -.092$

$A_3 = .375 - .330 = .045$

$A_4 = .650 - .770 = -.120$

$A_5 = .700 - .550 = .150$

$A_6 = .692 - .620 = .072$

$A_7 = .340 - .280 = .060$

MARC GUYLAINE II

	10°	20°	30°	40°
A_1 ρ	-.00420	-.00880	-.01550	-.02050
A_2 k_1	.00230	.00644	.01150	.01380
A_3 k_2	-.00059	-.00108	-.00158	-.00189
A_4 k_3	.00180	.00276	.00444	.00540
A_5 m	-.00300	-.00450	-.00600	-.00720
A_6 n	-.00194	-.00324	-.00360	-.00396
A_7 f	-.00036	-.00090	-.00156	-.00198
$\Delta GZ/B$	-.00599	-.00932	-.01230	-.01633
ΔGZ(cm)	-4.0 cm	-6.3 cm	-8.2 cm	-10.9 cm
ΔGZ(ins)	-1.6 ins	-2.5 ins	-3.2 ins	-4.3 ins

Figure I

REDUCTION OF RIGHTING LEVER DUE TO A FOLLOWING SEA

Dutch Trawler - IJM 44

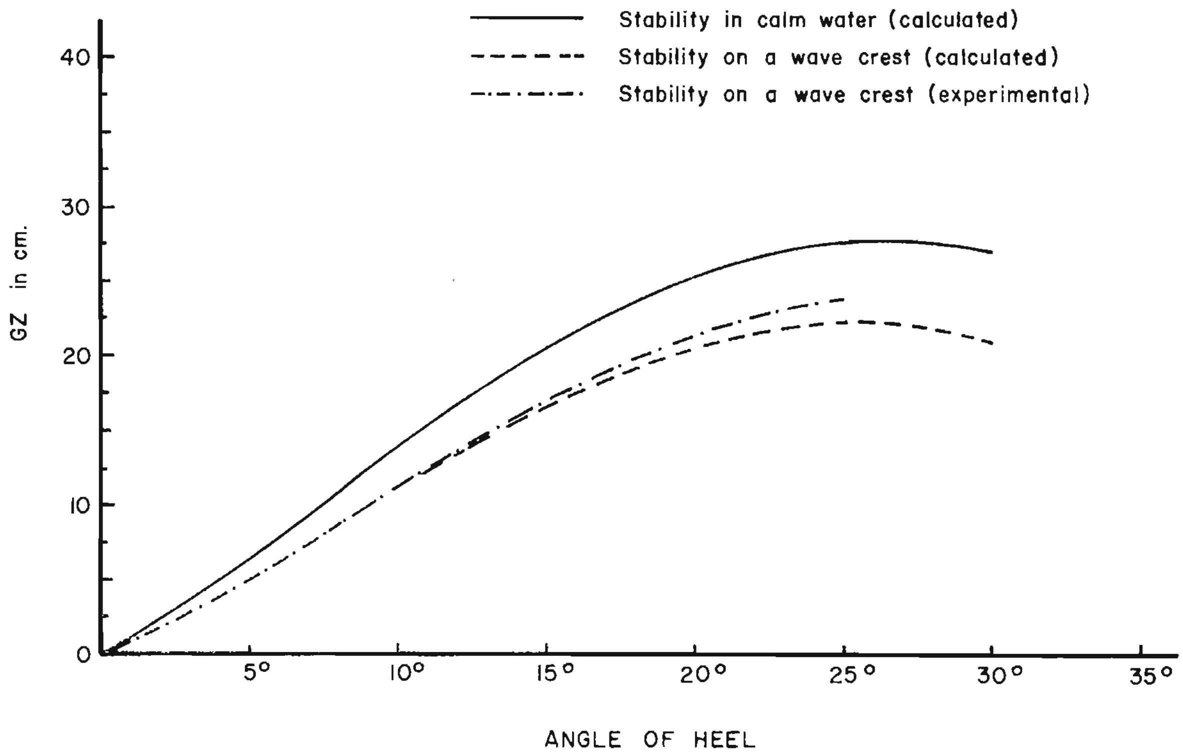

Figure 2

REDUCTION OF RIGHTING LEVER DUE TO A FOLLOWING SEA

MV "Marc Guylaine II" (Disp. 148 tons)

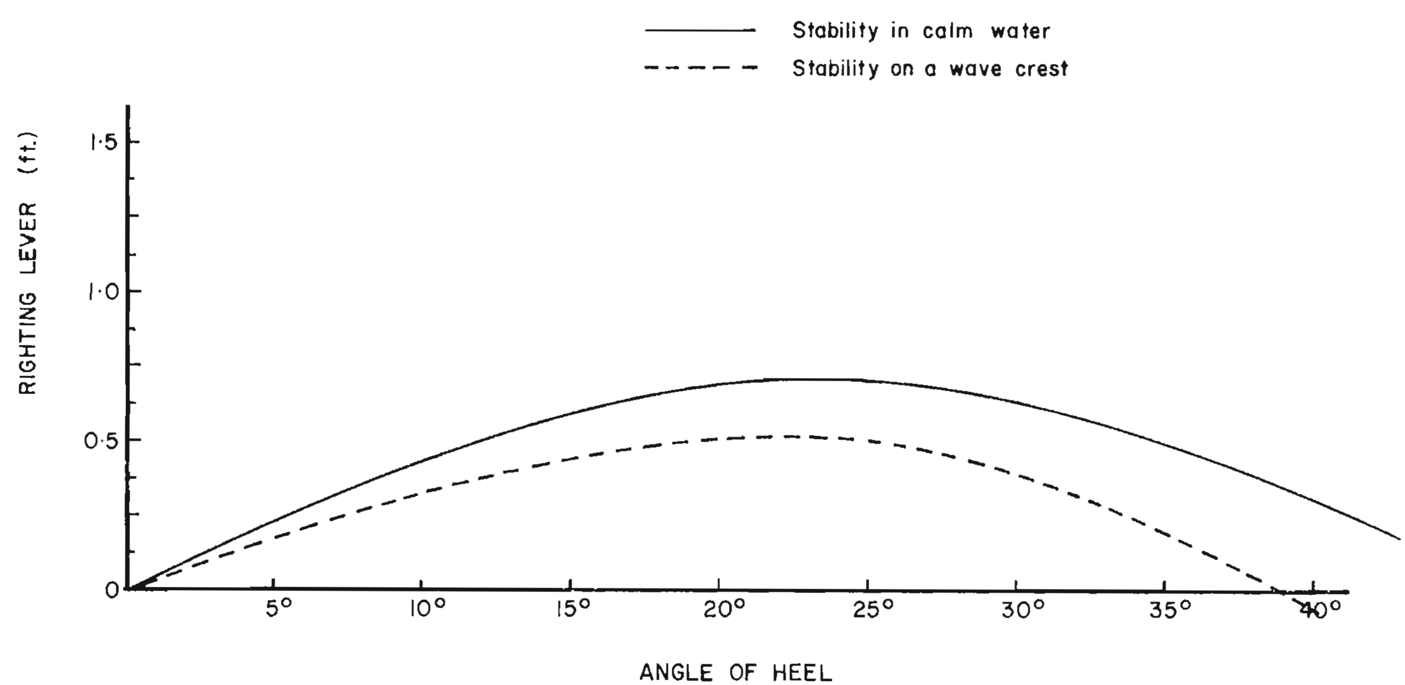

Figure 3

COMPARISON OF STABILITY CRITERIA

MV "Marc Guylaine II" (Disp. 143 tons)

AREA	RAHOLA'S REQUIREMENT	IMCO'S REQUIREMENT	COMMENT
A_1	15·00 Ft-Deg		Fails
$A_1 + A_2$		10·35 Ft-Deg	Passes
$A_1 + A_2 + A_3$		16·85 Ft-Deg	Passes
A_3		5·6 Ft-Deg	Marginal

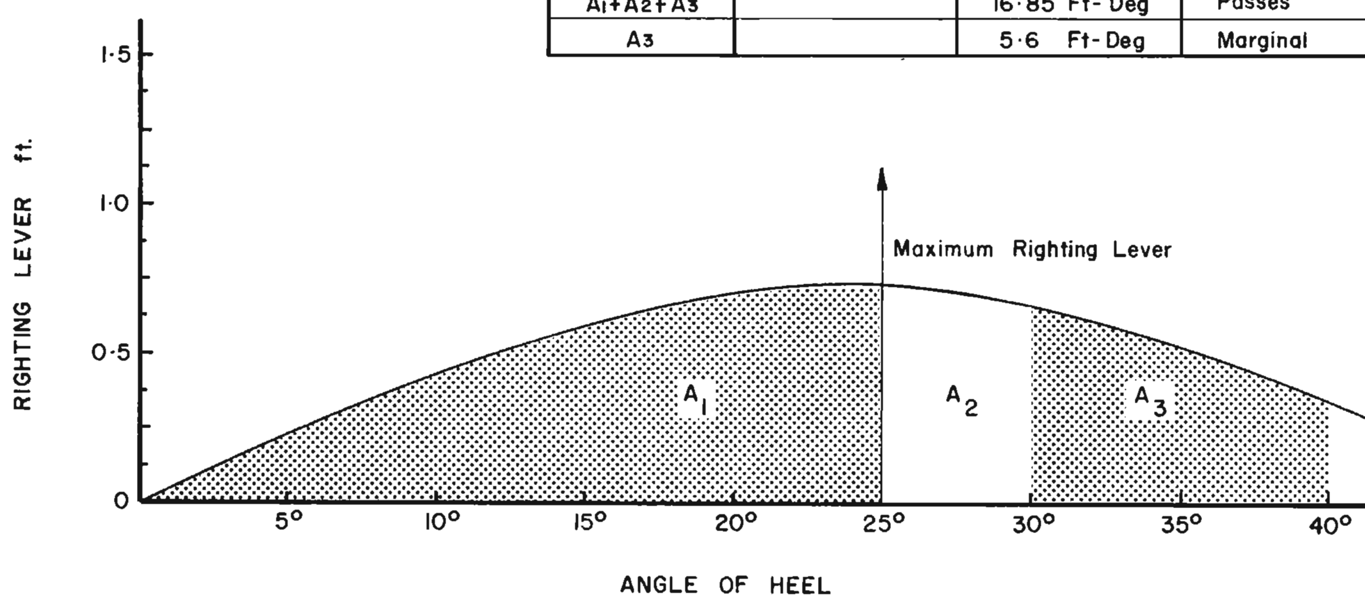

Figure 4

RIGHTING ARM CURVES

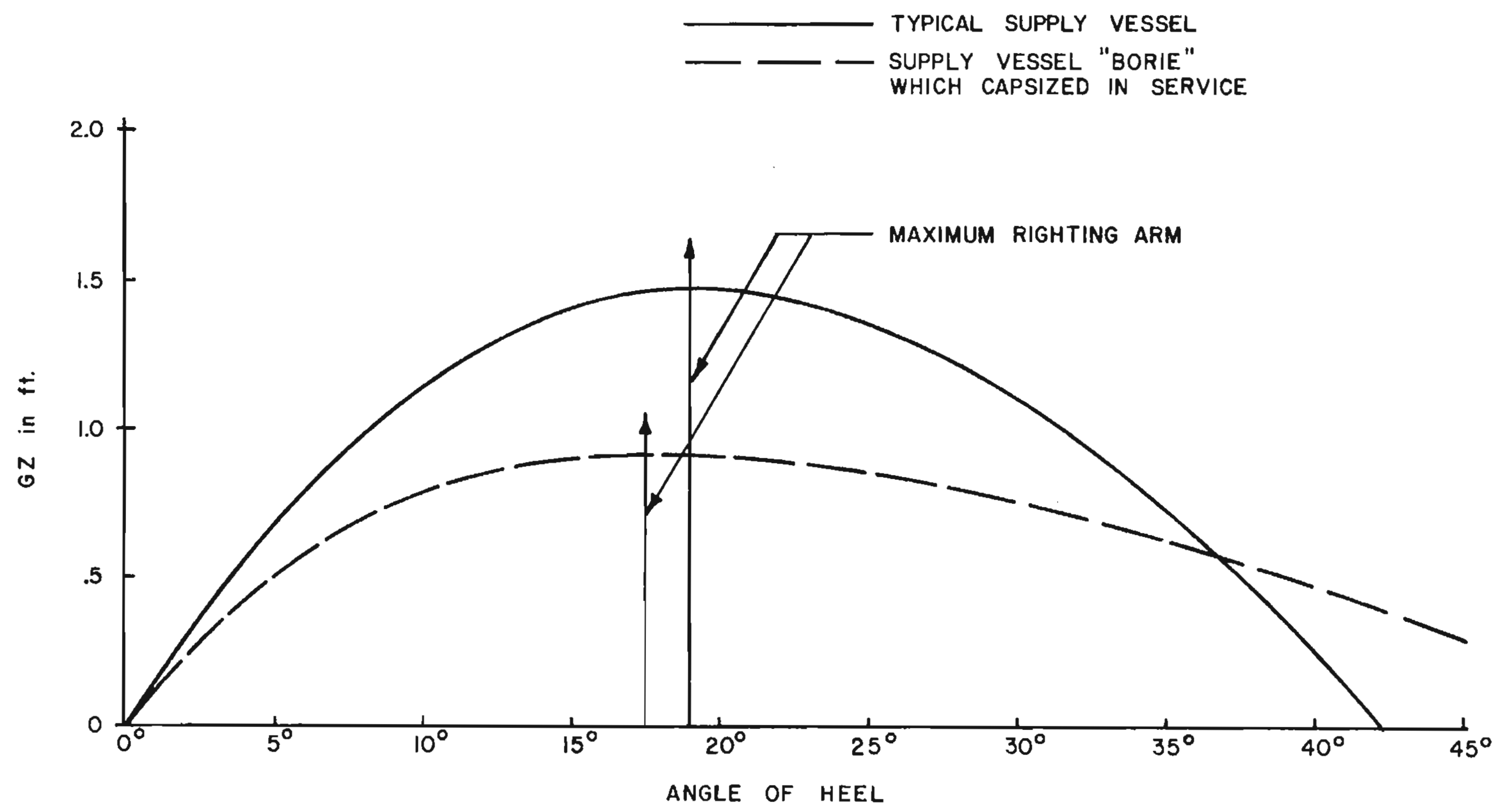

Figure 5

RIGHTING LEVER CURVES

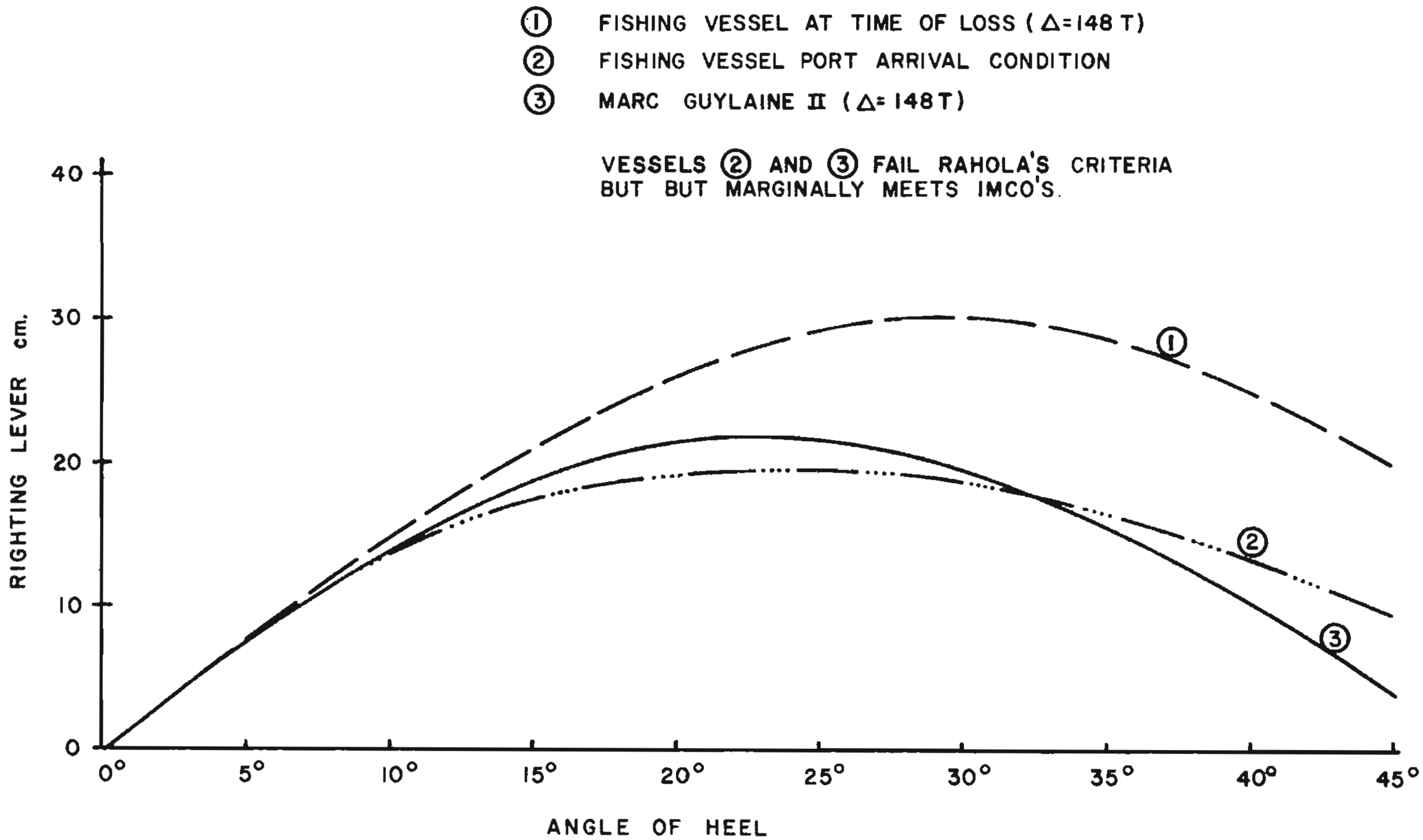

Figure 6

COMPARISON OF STABILITY CRITERIA

Fishing Vessel "EMMY"

AREA	RAHOLA'S CRITERIA	IMCO'S CRITERIA	COMMENT
A_1	15 FT. - DEGREES		FAILS
$A_1 + A_2$		10.35 FT. - DEG.	PASSES
$A_1 + A_2 + A_3$		16.85 FT. - DEG.	PASSES
A_3		5.6 FT. - DEG.	PASSES

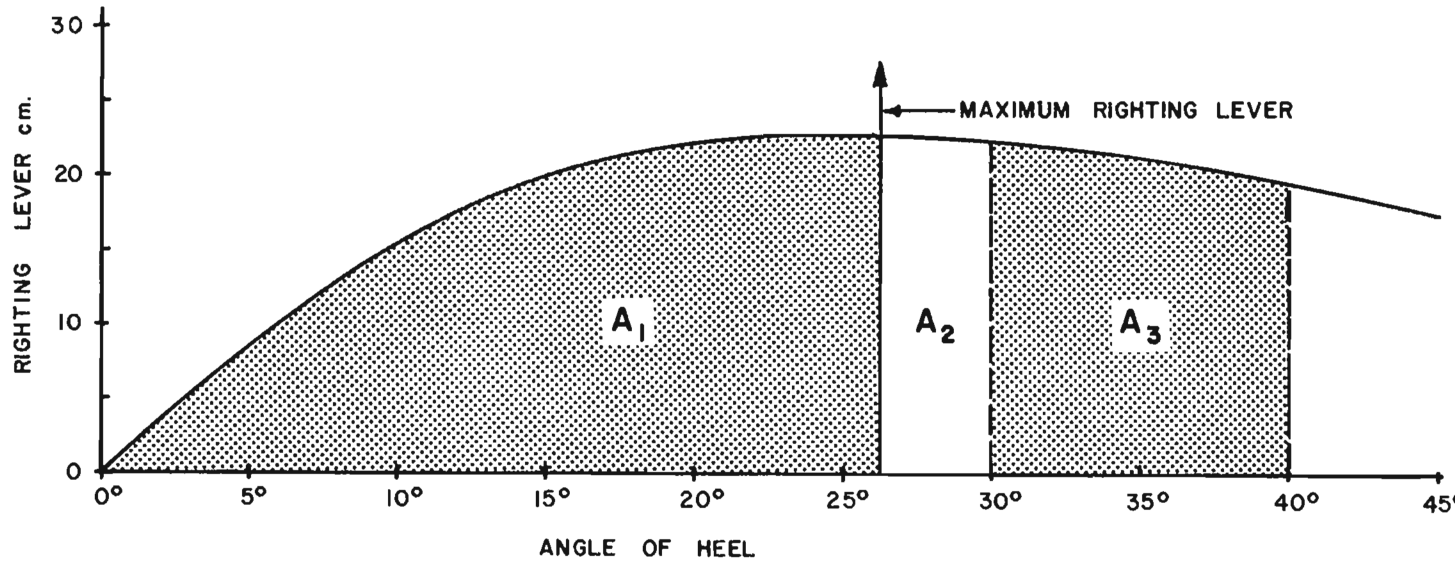

Figure 7

"EFFECTIVE" AREA OF STABILITY CURVE DUE TO TRANSIENT LOSSES.

MV "Marc Guylaine II"

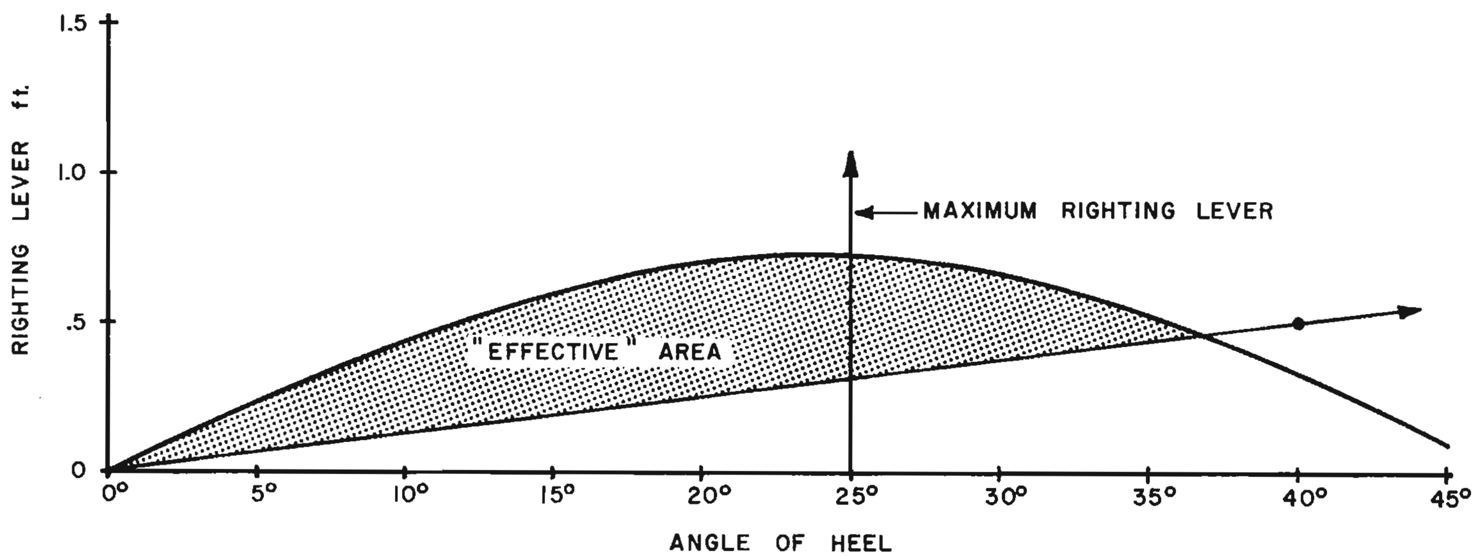

Figure 8

STABILITY CHARACTERISTICS

MV "Judy & Linda IV"