MODEL EXPERIMENTS AS A MEANS OF CHECKING THE ACCURACY OF CALCULATED STABILITY CURVES.

By Prof. Ir. J. W. BONEBAKKER.

Synopsis.

At the time when the methods for calculating stability curves now in common use were conceived, their accuracy was taken for granted, on the ground that the principles underlying these methods were correct.

In later years it appeared that the curves were always more or less approximate, even when they had been prepared with great care. The necessity of having accurate curves was not felt.

Professor Prihaska has recently made a thorough investigation of the discrepancies between the results of various calculating methods applied to the same ship. He came to the conclusion that approximate methods could be devised, whose results were equivalent to those obtained in the orthodox way, but in a much shorter time.

Råhola, on the other hand, has emphasized the importance of having accurate standards of minimum stability, especially for smaller vessels. But he seems to be unaware of the uncertainties disclosed by Prohaska.

In the present paper an attempt is made to show that really accurate stability curves can *be ascertained by carrying out model experiments. Consequently model experiments will enable us to detect the deficiencies and divergencies inhaerent to both orthodox and approximate calculating methods. It remains to be seen whether some of these methods may prove to be reliable.*

Finally, the application of minimum standards to stability curves, computed from model experiments, will eliminate the uncertainties which remain when these standards are applied to calculated curves of doubtful accuracy.

There are several methods for calculating ship stability curves in common use which are considered to be « exact », at least in theory. But it is becoming clear that in practice the uncertainties are fairly large. **Prohaska** (1, 2) has shown that the inaccuracies are even greater than might be expected. Calculations made for the same ship, using different methods repeated by different people, entailed rather diverging stability curves.

The causes of these inaccuracies may be briefly summarized :

1. an insufficient number of stations, waterlines and inclinations is used;
2. cross curves are faired through an insufficient or ill-positoned number of spots;
3. « k » values are plotted instead of MS values (residuary stability), see fig. 1;
4. the scale of the body plan is restricted by the size of the planimeter or integrator to be used;
5. errors in the readings of the planimeter or the integrator, even if taken several times for the same area;
6. the influence of the hull's ends (cruiser stern, propeller aperture, bossings, raked stem) is often neglected;
7. the influence of sheer, camber, hatchways and watertight erections is neglected or treated arbitrarily.

Prohaska (2) has set forth a new method for the rapid calculation of stability curves. A series of body plans, systematically varied, were drawn first and stability curves prepared with great care by « exact » methods for each body plan. In the second place, these stability curves were approximated by trigonometric expressions. By substituting in these expressions the characteristics of a particular ship form, its approximate stability curve is found at once. By repeating this for a number of sets of characteristics, representing every conceivable type of vessel, a set of tables was prepared from which an approximate stability curve for any ship can be lifted very quickly. This should be a great benefit in many respects.

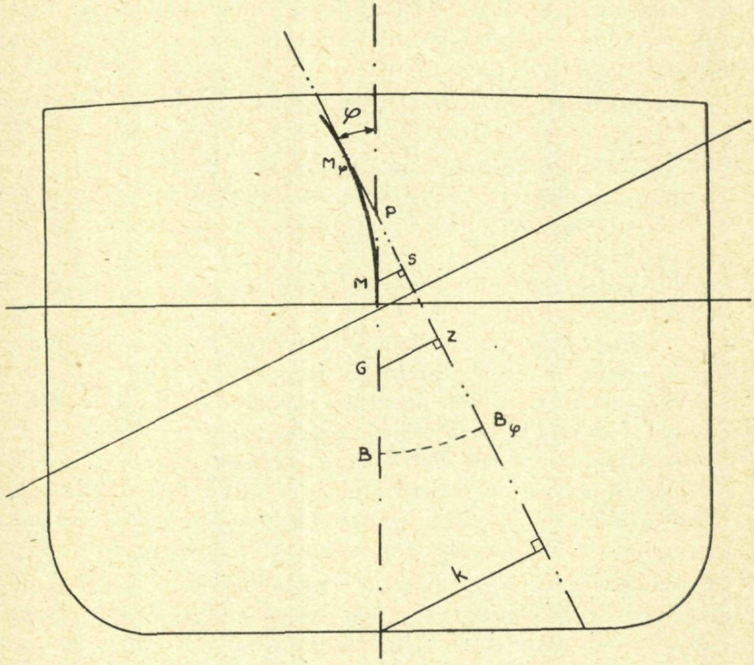
The agreement between the approximate method and the « exact » integrator method is very close.

However, a fixed standard for judging the accuracy of either method is still lacking.

Two questions present themselves :

I. is it necessary, or desirable, to be able to ascertain stability curves that are **really** exact ?

II. if the answer is affirmative, how can this be achieved ?



FROM : RESIDUARY STABILITY
BY PROF. C.W. PROHASKA
INST. OF NAV. ARCH. 1947
FIG. 1

I

There are many seagoing vessels whose stability characteristics will be always safe, provided that :

a. their design is in agreement with average practice,
b. the ships are handled appropriately.

Outstanding examples are tankers, as shown by **Burgess** (3), and dry cargo ships of the open shelterdeck type, excluding sizes below (say) 2.000 tons gross in both instances.

Ráhola (4) has probably been the first to treat the judging of the stability of a ship from a fundamental point of view.

Governing factors are :

a. main dimensions,
b. initial metacentric height,
c. maximum lever,
d. angle at which the deck edge immerses,
e. angle at which the lever is a maximum,
f. capsizing angle, or range of the stability curve,
g. dynamical stability, represented by the area of the statical stability curve.

Tankers of the usual long poop, short bridge and forecastle type are essentially low freeboard vessels. With ample initial metacentric height, the stability curves of the larger sizes will be satisfactory, even if superstructures are not taken into account. On the other hand the initial stability of open shelterdeck cargo ships may be quite small, but their dimensions and high freeboard entail an ample maximum lever at 35 to 40 degrees, a good range, and quite adequate dynamical stability.

For these cases, exact stability calculations may be considered superfluous.

Generally speaking, their curves will include a certain margin, and it is tacitly assumed that this margin will cover the inaccuracies of any calculating method, But we do not know whether this margin is large or small, simply because any standard of minimum stability is lacking.

There is, however, a marked difference between « large » and « small » vessels, although it would be difficult to fix their demarcation line. **Ráhola** rightly states :

« The smaller a vessel is, the more uncertain it becomes » to determine the **minimum** value of its initial metacentric » height » (p. 27). We might add : « and the more it is needed ».

Commentz (5), in the track of **Scribanti** (6), introduced the division of the stability lever into two components :

1. MG sin φ or « MG-stability », and

2. PM sin φ = MS or « residual stability » (Prohaska);

MG being the initial transverse metacentric heigt;

P, the « false metacenter », the intersection between $B_\varphi M_\varphi$ and BM;

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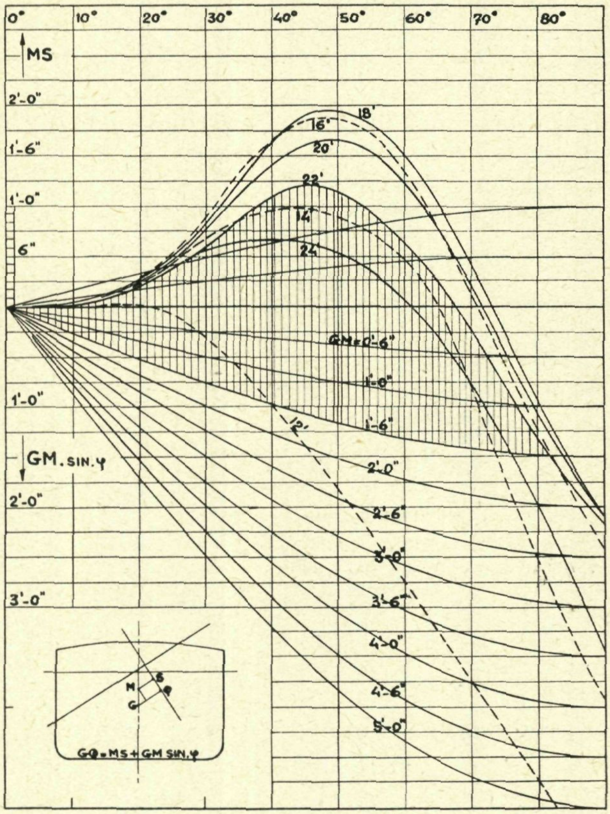
RESIDUARY STABILITY, BY PROF. PROHASKA.



M.S. DIAGRAM FOR SHIP USE.

FIG. 2

$M\varphi$ the shifting metacenter (see fig. 1).

For normal ship forms, with vertical sides for the greater part of their length at load line level, PM sin φ will be positive, and increasing in value within the deck edge range. As soon as the deck edge immerses the increment of the lever's residual component will diminish and sooner or later the component becomes negative. This can be very clearly represented in the manner proposed by **Prohaska** (1), shown in fig. 2.

Roughly speaking, in loaded condition the deck edge will *immerse at a list varying from less than 5 degrees to over* 20 degrees, depending upon the size and type of vessel, as shown in table 1 :

Table 1.

	type of ship	size	deck edge immerses at a list of about
1	open shelterdeck cargo . .	medium & large	20 degrees or more
2	tankers; poop, bridge and f'castle type cargo ships; having 40-45 % effective erections	medium & large	10 degrees
3	r.q.d. and flush deck vessels without bridge erection . .	small	5 degrees and less

The residual stability PM sin φ = $MS\varphi$ can be represented as a simple function of the variation of BM, as proposed by **Prohaska :**

$$(MS)\varphi = C_{RS} \; . \; BM,$$

C_{RS} being the « coëfficient of residual stability ».

Generally speaking, large vessels will have larger BM values than small vessels. Moreover, in group 3 of table 1, the deck edge range is very restricted. Consequently, in small vessels of low freeboard, the contribution of the resi-

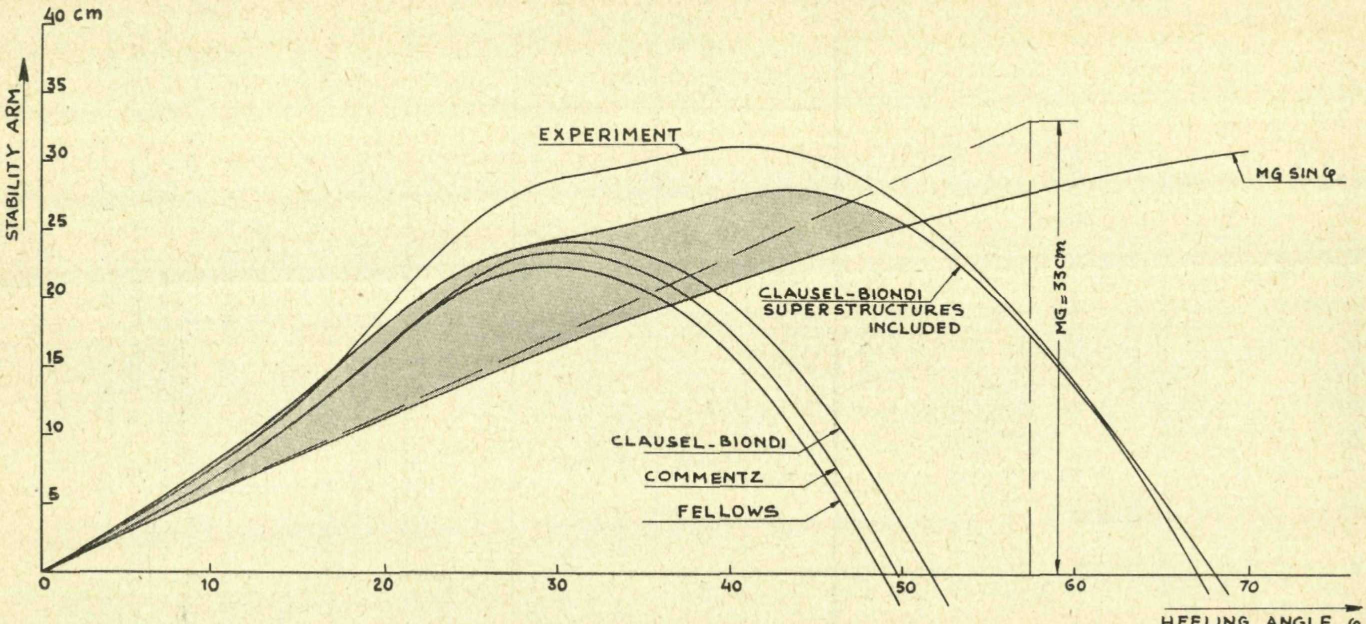


FIG. 3 STABILITY CURVES OF SMALL VESSEL

duary stability to the statical levers is negligible. These ships must have an ample initial metacentric height; often the contribution of their erections to the stability is indispensable.

The last remark requires some qualification.

Obviously, with small vessels, the influence of hatchways and effective superstructures on the shape and range of the stability curve is much greater than with large vessels. If the contribution of such erections to the stability is not taken into account in the former case, this may entail the application of too stringent requirements to the curve of the hull proper; with the result that the adoption of a large initial metacentric height seems to be inevitable, which may be detrimental in other respects and which might have been avoided if the erections had been taken into consideration.

At first sight, the small size open shelterdeck vessel might be considered quite safe on account of her high freeboard. But she, too, may be hampered by her main dimensions, especially if she has a low load waterline coëfficient. This is illustratted by a recent case, of which particulars are given in table 2 and fig. 3. The vessel in question is of the open shelterdeck type. An initial MG, in loaded condition, of 13″ = 33 cm. might seem to be sufficient. It will be gathered from the table and the stability curve that this is not so, unless her erections on top of the shelterdeck are effectively closed, and their contribution to the vessel's stability taken into account. That means an increase in range from 50° to 67°, and an increase in dynamical stability of 50 per cent.

In table 3 and fig. 4 the particulars of the small vessel under consideration are compared with those of a 9.000 tons deadweight cargo liner of the open shelterdeck type with short forecastle and the usual midship deckhouses for officers, crew and 12 passengers.

Table 2.

Single screw motor vessel, about 1.200 tons deadweight.

Machinery fitted aft; long poop and short forecastle on top of the shelterdeck.

Block coëfficient 0,57; load line coëfficient 0,71; MG = 13″ = 33 cm.

Stability curves, loaded condition (Clausel Biondi)	erections on top of the shelterdeck	
	not included	included
range of curves . . .	50 degrees	67 degrees
area of curves . . .	67 per cent	100 per cent
shaded portion of area, due to residuary stability	—	16 per cent
φ_m corresponding to maximum lever	30 degrees	43 degrees
MG sin φ_m . . . . . . PM sin φ_m . . . . . . total lever	16,5 cm = 6½″ 7,5 cm = 3″ 24,0 cm = 9½″	23 cm = 9″ 5 cm = 2″ 28 cm = 11″

Table 3.

size of vessel	small	large
block coëfficient δ . . load line coëfficient α .	0,570 0,712	0,664 0,762
MB . . . . BK . . . . MG	9′0″ = 2,74 m. 7′9¼″ = 2,37 m. 13″ = 0,33 m.	10′9″ = 3,28 m. 14′7¼″ = 4,45 m. 6½″ = 0,165m.
range, including erections	67 degrees	66 degrees
deck edge immerses at a list of	20 degrees	21 degrees
φ_m, corresponding to maximum lever	43 degrees	39 degrees
maximum lever . . .	11″ = 0,28 m.	15″ = 0,38 m.
natural period of roll .	8 sec.	17,5 sec.

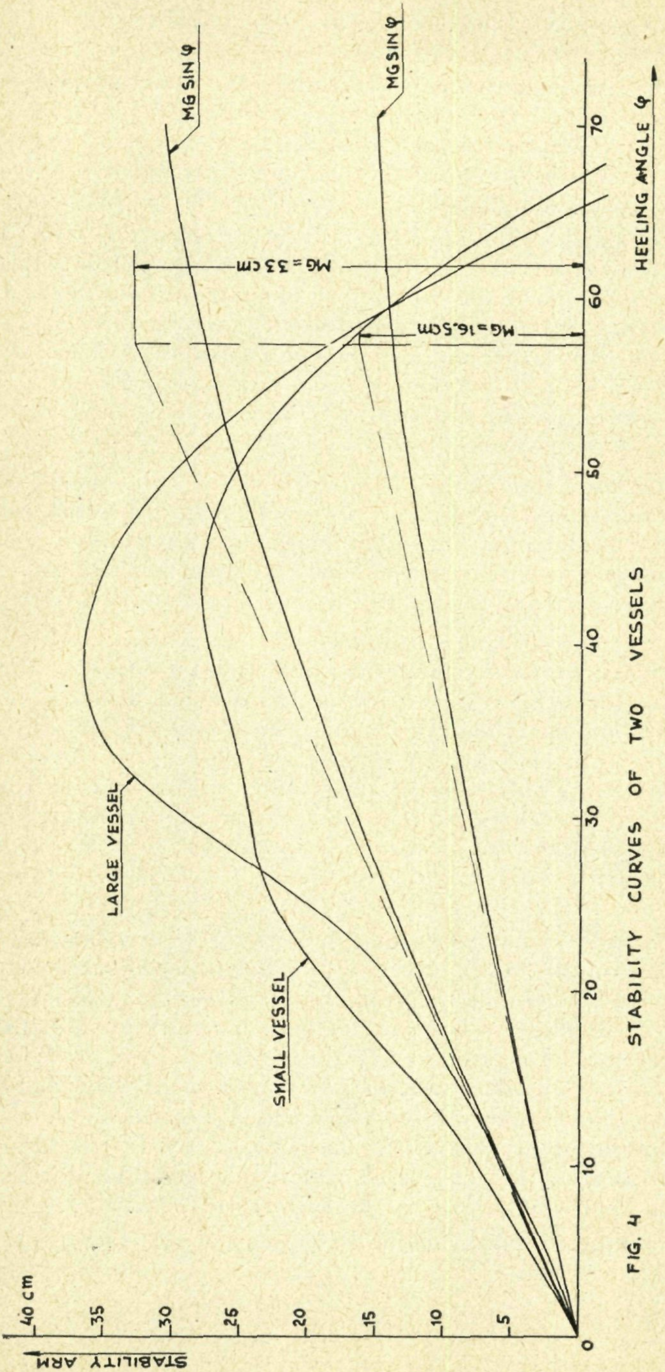


FIG. 4 STABILITY CURVES OF TWO VESSELS

The deck edge immerses at about the same angle of heel in both cases. But, though the small vessel's MG is twice the initial metacentric height of the large one's and her poop and forecastle are taken into account, the small ship's stability curve is still inferior to that of the large ship.

The smaller ship is inferior in another respect as well. Her natural period of roll is 8 seconds, as compared with the other's 17,5 seconds. Moreover, her lateral wind surface is, relatively, about 25 per cent larger. Consequently she may roll through larger angles in shorter periods. When sailing with an MG of 23″ her stability curve is satisfactory, but her natural period (port to starboard) is 6 seconds and she may roll excessively.

The large ship might safely sail with an even smaller MG, and she would roll comfortably with a larger initial metacentric height. On the other hand, for the small ship, the pertinent question presents itself whether her MG of 13″ could be further reduced safely, and exactly to what extent.

This representative example may do to show that it is necessary to have standards for fixing minimum stability curves for small vessels. Ráhola has derived such standards from a statistical analysis of disasters caused by inadequate stability. In applying his criteria we can only then feel sure when we are able to ascertain stability curves that are **really** exact. This can be achieved by carrying out model experiments, as explained in the next paragraph, in order to find the exact position of the buoyancy for any displacement, heel and trim.

It will be remembered that in 1948 the International Conference on the Safety of Life at Sea has framed several requirements concerning the stability of passenger ships in damaged condition. The usual methods for calculating stability curves for a damaged vessel, during the process of flooding and for her ultimate position, are known to be laborious and approximate. The results are even less accurate than the ordinary stability curves for undamaged conditions. Model experiments might be useful, either as a substitute for these calculating methods, or to check their (in)accuracy.

Finally, the Navy might be interested in experiments of this kind.

II

At the time when various methods for calculating stability curves were developed, their accuracy was taken for granted, or — to put it more precisely — their errors were considered to be negligible. This is quite understandable, because the principles underlying these methods are correct; often a reasonable degree of accuracy can be achieved. But — as stated before — they do not enable us to assign fixed limits beyond which a stability curve should be considered inadequate.

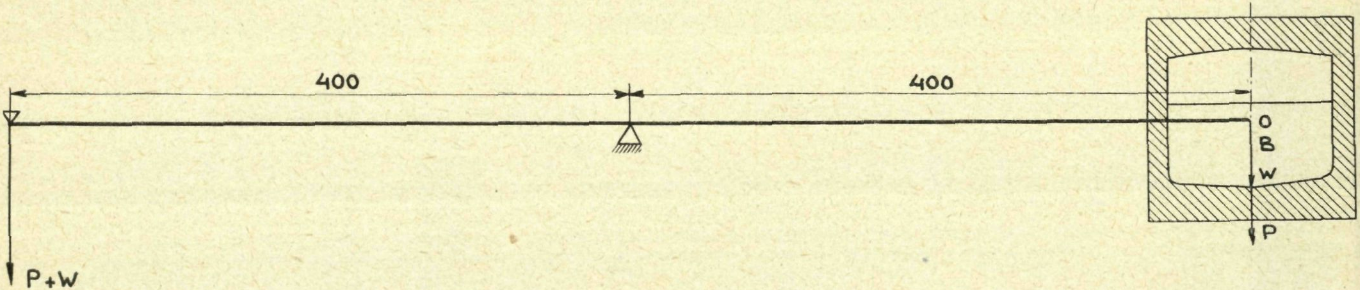
Ráhola publishes numerous stability curves in his book (4). But he never mentions the methods by which they were calculated; probably he has been unaware of the uncertainties disclosed by Prohaska (1). Even if it is assumed that these uncertainties are neutralized to a certain extent by his statistical analysis of disasters, it would still be more satisfactory if we could be certain that the stability curves under consideration were **really** exact (see Appendix).

At the University of Delft an apparatus has been designed and made for ascertaining accurately the position of a vessel's buoyancy for any displacement, or heel, taking into account the influence of camber, sheer,, hatchways and effective superstructures. Its principle can be found in a paper, read by John Heck before the Institution of Naval Architects (Transactions 1885), see fig. 5.

A mould is made, exactly to scale, of the ship's hull and effective erections. This mould can be filled with a quantity of water, equivalent to the displacement reprensenting the vessel's condition under consideration.

The empty model is fixed to the apparatus, which is a sort of balance, and the exact position of its centre of gravity ascertained experimentally. Then the model is partly filled with water, and the position of the centre of gravity of mould **and** water ascertained over a range of heels. This experiment can be repeated with different quantities of water, covering the whole range of displacements from zero to totally immersed vessel.

A mould, representing the small vessel already mentioned, has been made in Delft. An experimental stability curve



P = WEIGHT OF MOULD MODEL

W = WEIGHT OF WATER

O = CENTRE OF GRAVITY OF MOULD MODEL THE AXIS OF ROTATION PASSES THROUGH

B = CENTRE OF BUOYANCY OF WATER

FIG. 5A

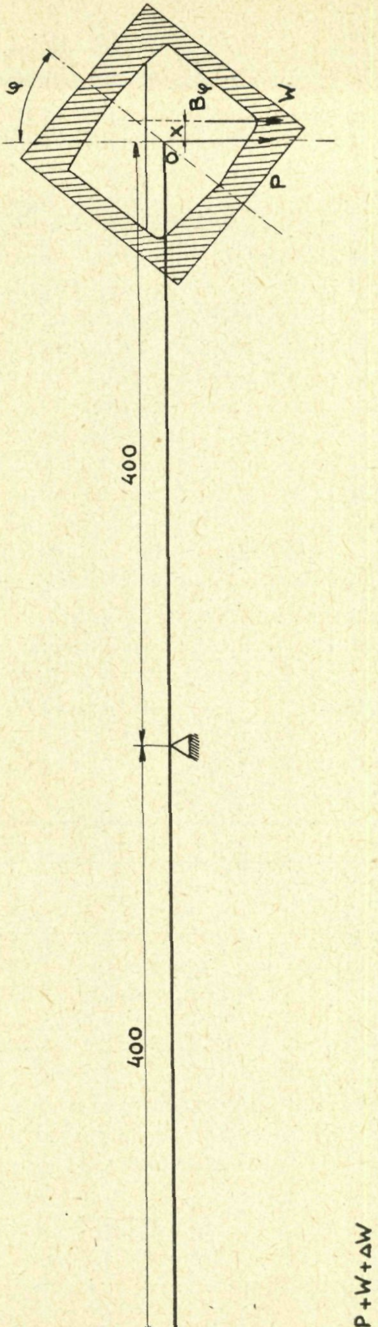


FIG. 5 B

for the loaded condition has been computed twice; the two curves cover each other exactly over the lower ranges, and differ slightly at larger angles of heel.

This experimental curve is also shown in fig. 3, for an assumed MG of 13″ = 0,33 m.

The apparatus described by Heck in his paper of 1885, made entirely of wood, was of very primitive construction.

It is rather curious to read that, at the time, the accuracy of the methods for calculating stability was taken for granted, it being greatly appreciated that the experimental curves did not differ materially from those calculated !

Nowadays, we should take the opposite point of view.

Much depends upon the accuracy with which the apparatus is made, and the sensitiveness of its balance. With the Delft apparatus, carrying a load of 30 kilogram on each arm, an additional one gram on one side will disturb the equilibrium. Light metals were extensively used in its construction.

The experiments should be repeated with other mould-models, and the resulting stability curves compared with those calculated by different methods — both so-called « exact » and approximate — before definitive conclusions can be reached.

Applying Rahola's criteria to the statical stability curves of fig. 3, the following is disclosed :

		Actual levers				
Angle of heel	Minimum lever	Fellows	Commentz	Cl. Biondi	Cl. Biondi	Experiment
		excluding erections			including erections	
20°	14 cm.	16 cm.	16 cm.	18 cm.	18 cm.	19 cm.
30°	20 cm.	22 cm.	23 cm.	24 cm.	24 cm.	28½ cm.
40°	20 cm.	16 cm.	17½ cm.	19½ cm.	27 cm.	31 cm.

The differences between the Fellows, Commentz and Clau-Clausel-Biondi curve (excluding erections) is dubious. When the erections are taken into account, the Clausel-Biondi and the experimental curve are both adequate.

The differences between the Fellows, Comments and Clausel-Biondi curves (excluding erections) are not large, and they agree in character. The last remark applies also to the experimental and Clausel-Biondi curves (including erections). But the differences in levers between, say, 25 and 45 degrees are of the order of 15 per cent; and the experimental curve's area is about 10 per cent larger than the calculated curve's.

There is a way to ascertain really exact stability curves for any range of heels and displacements. If the mould-model could also be fixed to the apparatus at various angles of trim, a universal set of cross curves could be computed, covering all ranges of displacement, heel and trim. This would simplify the study of a vessel's stability in damaged conditions — as far as the location of the buoyancy is concerned — the influx of water being treated as an « added weight ».

Model experiments enable us :

a. to get an absolute standard for judging the accuracy of both approximate and so-called « exact » methods for calculating stability curves;
b. to ascertain accurately the contribution of a vessel's sheer, camber, hatchways and effective superstructures to her stability.

When these contentions are fully realized, it will be agreed that a much closer determination of the minimum amount of stability than hitherto possible could be attained. The expediency of doing so has been amply demonstrated by Ráhola for small, **low** freeboard vessels. From the case treated in this paper it would appear that the same applies to small, **high** freeboard vessels. Amongst the larger types of ships, of the passenger or mixed class, there will doubtless be meny cases where a close determination of minimum stability is of equal importance.

There is a wider scope for model experiments on stability.

Mention has been made of the susceptibility of small, high freeboard vessels to excessive rolling. Experimental investigation of both the extent and the period of rolling through large angles, caused by known heeling moments, is required to cover the gaps in our knowledge of this phenomenon.

A more elaborate apparatus for model experiments on stability is described by Werckmeister (7). A similar apparatus, of improved construction, has been acquired by the University of Delft. Floating models are tested by registering the heeling couple at specific angles of heel. The model is free to change its trim, just like the actual ship, and these changes can be recorded too. The apparatus has the same merits as the mould-model; it takes less time to compute a stability curve from the observations because heeling couples are registered, but its range is restricted to 100 degrees.

At the moment the stability of lifeboats in light, loaded, and partially flooded condition is being investigated.

Acknowledgement.

The Author wishes to acknowledge, with thanks, the support received from the « Delfts Hogeschoolfonds » (University Research Fund), which enabled him to get the investigation started, and the valuable cooperation of his assistant, Mr. Pereboom.

Further investigations are being carried out under the auspices of the « Studiecentrum T.N.O. voor Scheepsbouw en Navigatie », the Dutch equivalent of the B.S.R.A.

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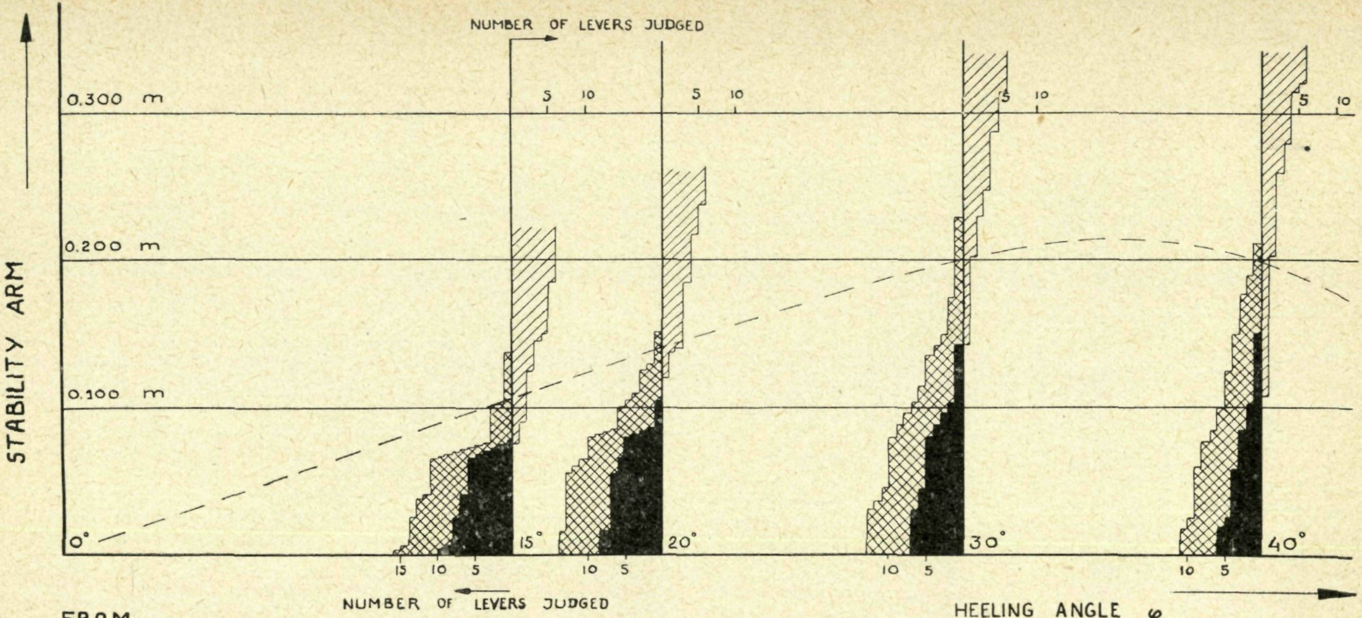

FROM:

THE JUDGING OF THE STABILITY OF SHIPS AND THE DETERMINATION OF THE MINIMUM AMOUNT OF STABILITY.
BY J. RAHOLA

ADEQUATE VALUES OF $\overline{GH}$
CRITICAL " . .
INSUFFICIENT . " .

FIG. 6

APPENDIX.

Ráhola's approach to his subject : « The judging of the stability of ships and the determination of the minimum amount of stability » deserves to be stated here, referring to fig. 30 page 65 of the book (reproduced in fig. 6).

Stability levers at 15° - 20° - 30° - 40° angle of heel were ascertained for each of the investigated cases. For each angle of heel, these levers could be grouped under one of three headings : adequate, dubious, insufficient, and plotted in a frequency diagram. At 30° list there is only one case where a lever of more than 200 mm. was considered dubious, and one other case where a lever of less than 200 mm. was considered adequate. In five instances, a lever of 300 mm. or less was considered adequate. Out of ten cases with levers of 60 mm. or more, five were considered insufficient and five dubious,

Looking at the diagram, it is quite clear that a very definite minimum curve of levers can be drawn, as shown by the dotted line. Ráhola confined himself to vessels navigating « under the conditions prevailing on the great lakes and the waters adjacent to our country » (Finland). It would be interesting if the accidents of other types of ships were investigated in a similar way.

REMARKS TO PROFESSOR BONEBAKKER'S PAPER.

By Prof. G. VEDELER.

I am very glad to see Professor Bonebakker's reference to Rahola's dissertation of 1939, which I think is not yet so well known as it deserves. To my opinion this book is the most important work on stability which has been published during the last thirty years. I may add that it is also easy to read, being based on statistical probability in connection with casualities. I have tried its recommendations in connection with cases of capsizing of small ships on the Norwegian coast recently, and it seems to be a very good guide.

Personally I am not as pessimistic as Professor Bonebakker with regard to the accuracy of stability curve calculations, that is when the calculation is properly made with due regard to erections etc. and according to the method recommended by Commentz and Prohaska by adding MG- and MS-stabilities. But still model experiments may be of great value if they are properly carried out, and I think many interesting questions in connection with stability can be studied by such experiments. The greatest value of such experiments may, however, be for the teaching of students in naval architecture.