COMPUTATION OF THE TRANSVERSE STABILITY OF A SHIP IN A LONGITUDINAL SEAWAY

C. E. B. Boden and R. F. Halliday

PART I: Using a Hydrostatic Analogue

ABSTRACT.

Using an inexpensive model and a number of small perspex tanks containing water, an inclining experiment was carried out to determine the stability of a ship in a seaway. The changes in pitch and heave were automatically reproduced and the only doubtful assumption made was that a hydrostatic distribution of pressure existed under the waves. The work of Paulling (2) shows this assumption to be reasonable for large angles of heel.

INTRODUCTION.

When the stability of a tuna fishing vessel was checked recently, the expenditure of time required to calculate righting arms for the hogging condition was almost beyond economic limits. In searching for a simpler method model tests were considered. Halliday suggested moulding a shell in plastic, subdividing it by a large number of bulkheads and supporting it on a multi-component balance. Flooding the compartments to various levels corresponding to the wave ordinates would reproduce the buoyancy and moments, but with the sign reversed. When this idea was worked out on paper so that the adjustment of the various levels was automatic, it was apparent that the model would be expensive to construct and the whole apparatus rather complicated. Boden, on the other hand, suggested that the body plan of the ship be reproduced on a three quarter inch thick sheet of foamed polystyrene, the cross-sections cut out with a bandsaw and then fastened in their proper relative positions to a backbone of thin walled aluminium tube. Originally the cross-sections were to be selected according to the spacings given by Tchebycheff's Rule so that the results obtained with the model would correspond to an integration along the length of the ship according to this rule. Variation of the thickness of the slabs of foamed polystyrene would permit a Simpson's Rule integration. The discontinuous nature of the model to be used would permit each slab to be floated in an individual tank of water. The levels in these tanks could be made equal by opening cross-connections, or varied to correspond with the ordinates of a trochoid representing an ocean wave. When the model was suitably trimmed, a series of inclining experiments could be carried out and hence the righting arms determined for various angles of heel.

The suggestion offered by Boden appeared the simpler of the two proposals and was therefore put into practice. The use of the remarkably light weight, yet readily available, foamed polystyrene provided a sufficient margin of buoyancy to carry the connecting structure, the balance weights for adjustment of the centre of gravity, the beam and weights for the inclining experiment, as well as a protractor, plumb line and bob to indicate the angle of heel. A sketch of the model is shown in figure 1. (Of course, more than four sections are required for any degree of accuracy to be achieved, and a six section model was used for the first trial. Later a ten section model was substituted.) The arrangement of the tanks is shown in figure 2.

In practice the inclining experiment was carried out with ease by shifting weights from one side of the weight beam to the other, the plumb line and protractor being suitable for the measurement of the angle of heel. The centre of gravity was located by supporting the model on needle point bearings, clear of the water, and going through the procedure of the inclining experiment a second time. A cathetometer was used to determine

The adoption of one of Tchebycheff's Rules in the present case has the advantage of using samples of the same weighting and which may be represented in the model by slabs of the same thickness. Unfortunately a special body plan must be drawn for cross-section spacings corresponding to the rule. The use of Simpson's Extended Rule avoids the latter difficulty but requires slabs of different thickness to make up the model, a requirement which is not only inconvenient from the mechanical point of view but effectively renders the sample spacing less uniform and may accentuate the effects of some discontinuities. For example, the distribution of transverse righting moment along the length of a ship with a high forecastle and low main deck is shown in figure 4. The forecastle ends just forward of the midship section and is missed by the heavily weighted central ordinate with the result that the integration by Simpson's Rule is too low by about 10 percent. Had this ordinate just caught the forecastle, the integration would have been high by a similar amount. It would appear desirable, therefore, to add to the slab at the midship station a superstructure of reduced thickness to roughly compensate for this error. If such adjustment is not attempted, then it would be better to use Tchebycheff's 10 ordinate Rule or even the Trapezoidal Rule.

In order to test the experimental method further, it was desirable to compare the results against those obtained using an Amsler integrator(3). As the latter were based on Simpson's Extended Rule for 11 ordinates, without adjustments, the second model followed this scheme. The agreement was satisfactory.

CONSTRUCTION OF THE MODEL.

The slabs representing cross-sections of the ship were cut on the patternmaker's bandsaw from three quarter inch thick sheets of foamed polystyreme. Because the bearing strength of this material is so poor, timber or glass fibre inlays were provided where the quarter inch diameter struts were inserted to connect the slabs to the backbone of three quarter inch thin walled alumimium tube. Cold setting epoxy resin was used to glue the parts together. To bind the friable surface of the foamed polystyrene the slabs were painted with shellac dissolved in spirits. The load water line was marked on each slab. The struts were inserted in holes drilled right through the backbone and fastened with epoxy resin. At this stage the model was set up on a cast iron marking off table and the components held accurately in alignment while the glue set. In similar manner the struts for the balance weights, the weight beam and the protractor were attached. Dress-maker's pins were used as pivots for the movable ballast weights which were suspended by cotton thread, and for the plumb line. The main ballast weights, limited by the margin of buoyancy and therefore set low, were added when the model was trimmed while floating in the tanks. The tanks themselves were fabricated from perspex sheet.

EXPERIMENTAL PROCEDURE.

The tanks were filled with water and detergent added to reduce surface tension. Short syphons of transparent tube were used to connect the tanks and ensure a uniform water level while the model was trimmed to float at the design load water line which was marked on each slab. As much movable ballast as seemed practical was equally distributed between the two sides of the weight beam, and then the main ballast adjusted to give the required trim and a suitable margin of stability. If the model is too stiff then the movable ballast will be insufficient to secure, say, seventy degrees of heel. On the other hand, if the model is too tender, it will be difficult to achieve any reasonable accuracy in the inclining experiment.

The major advantage of the model technique over the drawing board method is the fact that, within the accuracy of the integration rule chosen, the model will automatically adjust itself to equilibrium in pitch and heave. Therefore it is most desirable that the centre of gravity of the model should not be too far removed from the position corresponding to the centre of gravity of the ship. However the stability in pitch is usually so high that the small variations implied by the suggested adjustments are unlikely to significantly affect either longitudinal stability or trim, and may therefore be tolerated.

When properly trimmed and the main ballast firmly attached, the model was carefully weighed as a check on its construction and adjustment. This being satisfactory the centre of gravity was found: The model was supported on needle points which engaged the inside of the crown of the tubular backbone so that it was clear of the water. An inclining experiment was then carried out, and as the angle of heel was small, it was determined by measuring the change in relative heights of the pins carrying the movable ballast. A more suitable location of the pivot points would have resulted in sufficiently large angles of heel to be measured by the plumb line and the protractor. The distance from the pivot point to the centre of gravity is

$$\frac{w}{W} l \cot \theta$$

where w is the weight of the movable ballast,

l the transverse distance it is moved,

W the weight of the model, and

θ the angle of heel.

The height of the pivot points relative to the load water line was determined accurately, (the cathetometer is most useful for this kind of measurement,) and then OG the height of the centre of gravity above to the load water line determined.

With the model floating freely in the water a series of inclining experiments were carried out in the same manner. The righting arms GZ are given by

$$\frac{w}{W} l \cos \theta$$

and can be scaled up for the ship according to the reciprocal of the linear scaling adopted for the model cross-sections. It should be noted that the longitudinal scale need not be the same as the transverse and vertical scale, and does not enter into the calculation.

After heeling the model to about 70 degrees with a uniform water level in the tanks, the syphons were removed and the levels adjusted to correspond with a trochoidal wave having a crest at station 5 and troughs at stations 0 and 10. For this hogging condition the inclining experiments were repeated. In a similar manner the sagging condition was investigated.

RESULTS.

A comparison between the results obtained from the model tests and those obtained using the Amsler integrator showed reasonable agreement. In general discrepencies were less than 5 percent and this would suggest that the model technique is adequate for most purposes.

CONCLUSIONS.

Once the model has been constructed the righting arms for various sea conditions and various displacements can be obtained within a few hours. Modifications to the lines are easily incorporated in the model without completely rebuilding it. Therefore it is concluded that the model test is in general an economical method for determining transverse stability, and most certainly so when marked differences between the fore body and the after body lead to a sufficient disturbance in pitch to influence the results.

The ease with which this problem can be handled by a large, high speed, automatic digital computer seems to imply that such model tests are already superseded. But not everyone is so fortunate as to have ready access to such a machine, and where computer time must be purchased from an outside organisation, the fees are such as to cover the cost of the model. Considering the convenience of having the analogue set up next door to the drawing office, there is still a strong case for the model test.

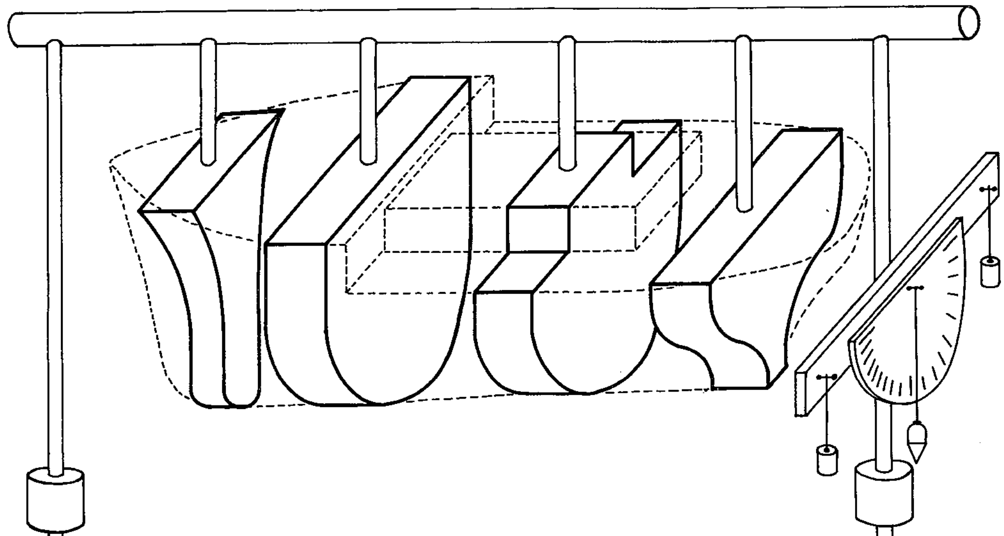


Figure 1.

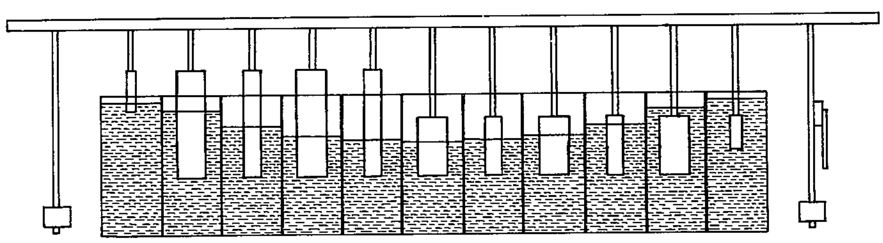


Figure 2.

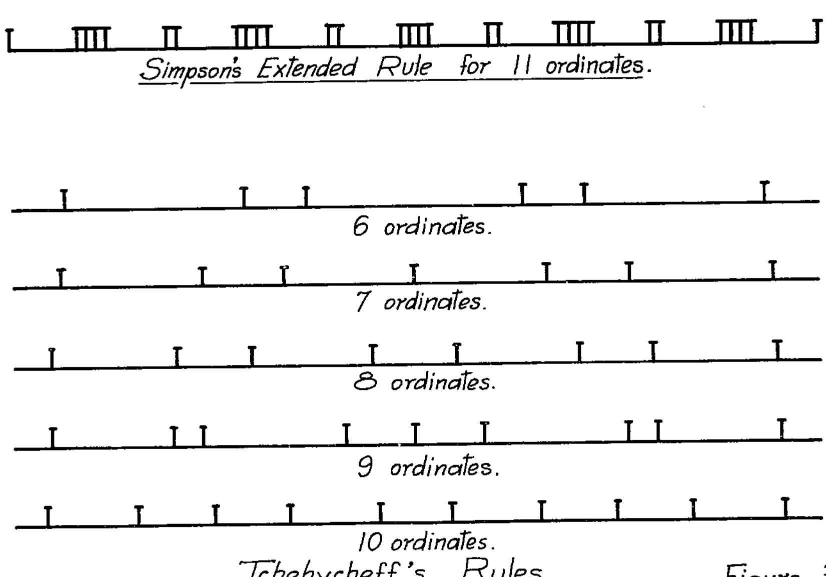


Figure 3.

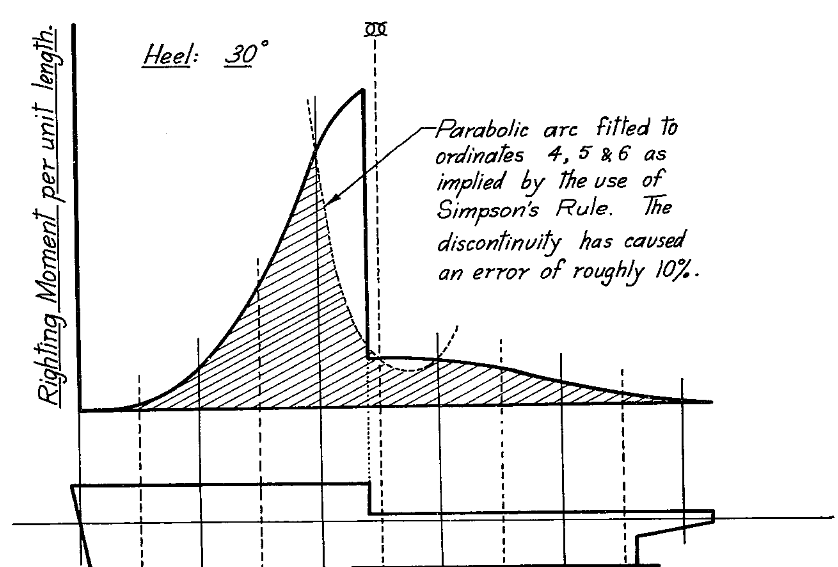


Figure 4.

COMPUTATION OF THE TRANSVERSE STABILITY OF A SHIP IN A LONGITUDINAL SEAWAY

PART II: Using an Automatic Digital Computer.

ABSTRACT.

Assuming a hydrostatic distribution of pressure under the waves, the computer was programmed to calculate the righting moment of a ship in still water and also when hogging and sagging in a longitudinal seaway. Automatic adjustments are made to heave and pitch in order to maintain, respectively, the initial displacement and the initial longitudinal position of the centre of buoyancy.

For each increment of the angle of heel this computation involves two inter-acting iterations depending on two integrations through the immersed volume, as well as the integration of the righting moment, and all these must be based on sampled data. Such computations tend to require too much machine time to be economically justifiable. Therefore the programme contains some interesting features which successfully combine to reduce the running time to about half an hour, being a thousandfold improvement on the first trial.

As an example, the stability of a tuna fishing vessel is computed.

INTRODUCTION.

Most ships are sufficiently near to being symmetrical about the midship cross-section that pitching may be ignored for the purpose of calculating the righting moment when the ship is heeled. Commonly used methods are described in standard text-books (1) and involve a certain amount of trial and error in the adjustment of heave so that buoyancy and weight are in equilibrium. When another stage of trial and error must be added to adjust pitch so that the moment of buoyancy and the moment of weight about a transverse axis are also in equilibrium, then the task of manual computation becomes extremely tedious. In fact, Paulling (2) found that "it would be more expedient to investigate a range of ship and wave parameters experimentally rather than theoretically."

Recently the stability of a rather unsymmetrical tuna fishing vessel was checked (3) using an Amsler integrator and the computing time was 160 man hours. At the Sydney University Ship Model Tank, Boden and Halliday, seeking a more economical solution, set up a hydrostatic analogue. While this experiment was in progress, it was pointed out to the authors that the University's Automatic Computer would surely carry out this computation even more efficiently. Accepting the challenge Halliday programmed "Silliac" according to a commonly used simplified coding scheme known as A 10, and discovered that the machine time required would be several thousand hours. As this was quite beyong all economic limits, the programme was re-written to use the fixed point binary arithmetic for which the machine was designed, instead of the floating point decimal arithmetic of A10. Further, both the mathematical approach and the programming technique were improved to the extent that the calculation which had taken 160 man-hours to perform was repeated in four machine-minutes. Taking the cost of one machine-minute as comparable with the cost of one man-hour, and allowing eight hours for preparing a modified table of offsets, punching it on teleprinter tape and checking for errors, the cost is cut by more than 90 percent. Since the digital computer print-out includes pitch and heave, it can be readily spot checked, using the Amsler integrator, without having to repeat any trial and error process. The final version of the programme repeated the calculation for three sea conditions for each of three conditions of loading and

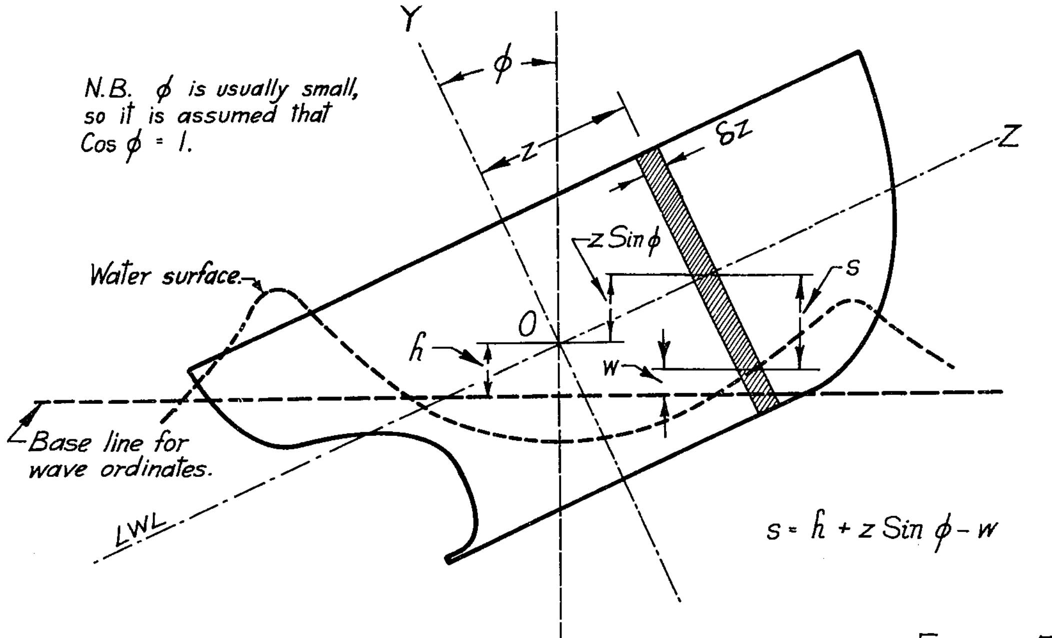


Figure 5.

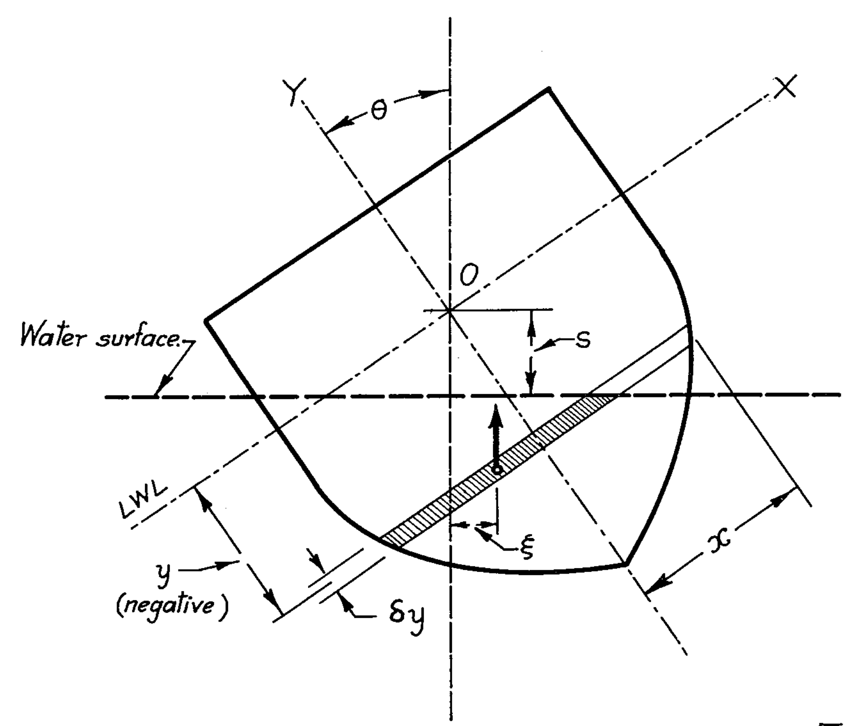


Figure 6.

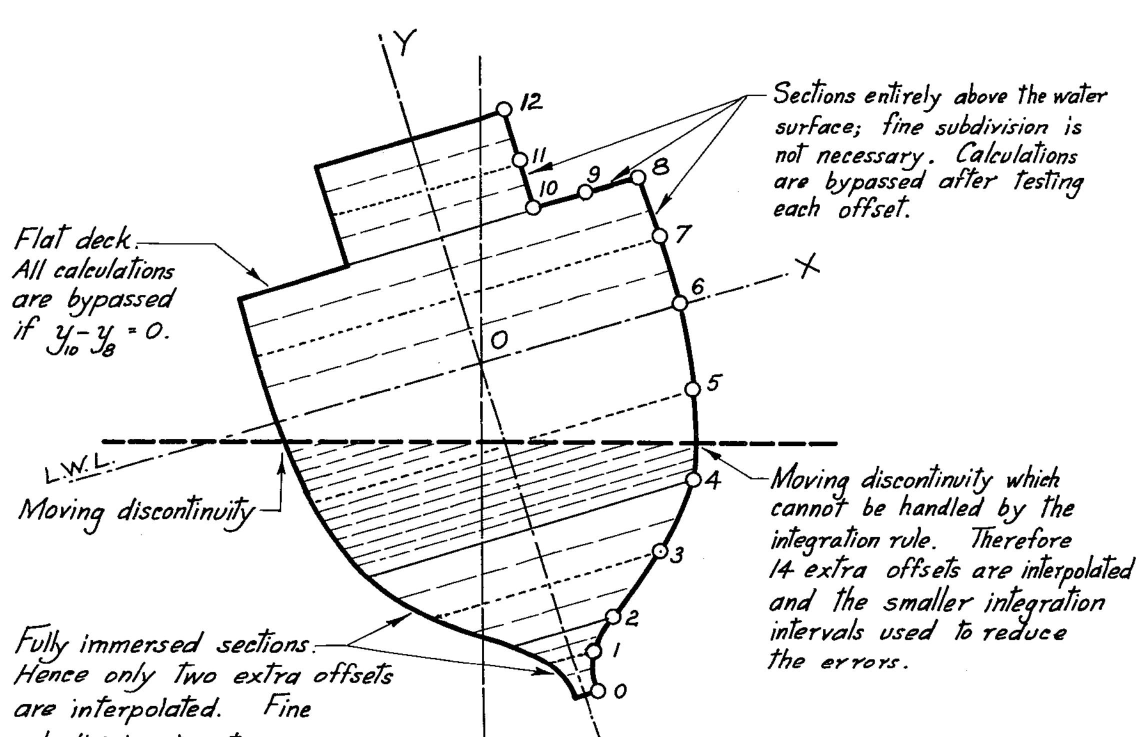


Figure 7.

ran for 25 minutes.

The assumption of a hydrostatic pressure distribution under waves is justified by Paulling (2) who concludes that it "yields results sufficiently accurate for engineering purposes ----" at large angles of heel. He points out, however, that in calculating the initial metacentric height in waves, the hydrodynamic effects must be considered.

THE MATHEMATICAL APPROACH.

The shape of the hull and water-tight superstructure can be presented to the machine only as a set of representative points on the surfaces. They are defined by their co-ordinates referred to a set of three orthogonal axes fixed within the hull. When the ship is trimmed to the standard condition in still water, the origin is located in the midship section on the longitudinal or Z axis at the load water line. The Y axis is vertical and the X axis is horizontal and transverse. The x co-ordinates correspond to the offsets, the y co-ordinates to the water-planes and the z co-ordinates to the stations. Figures 5 and 6 illustrate this co-ordinate system and help to define the symbols used. It will be appreciated that the following treatment is but a variation on a well known theme recorded in most text-books on naval architecture.

Consider a cross-section at a station defined by a particular z co-ordinate. If h is the height of the origin above the wave base line, w the wave ordinate and $\emptyset$ the angle of pitch, then at z, the height of the Z axis above the water surface is

$$s = h + z \sin \emptyset - w$$

Let the cross-section be regarded as a plane lamina of unit thickness divided into thin strips of length 2x and depth δy. The depth of immersion of the lower end of such a thin strip is

$$s + y \cos \theta - x \sin \theta$$

where θ is the angle of heel. As the algebraic value of y increases, this depth of immersion changes sign indicating that no portion of the strip is immersed. This change of sign is detected by the computer and used to set y^*, the upper limit for the integrations. The length of strip immersed is the lesser of

$$2x$$

and

$$(s + y \cos \theta - x \sin \theta) \div \sin \theta$$

Calling this immersed length x', its volume is

$$\delta\delta v = x' \delta y$$

The lever available to this element of buoyance is

$$\xi = (x - \tfrac{1}{2}x') \cos \theta + y \sin \theta$$

so that on a volumetric basis the moment is

$$\delta\delta M_r = \xi x' \delta y$$

The immersed volume for the cross-section will be

$$\delta v = \int_{y_0}^{y^*} x' \delta y$$

and the righting moment will be

$$\delta M_r = \int_{y_o}^{y^*} \xi x' \; \delta y$$

The lower limit of integration is, of course, the draught. If the cross-section has been divided by various water-planes at levels

$$y_o, \; y_2, \; y_4, \; y_6 \ldots\ldots\ldots\ldots$$

and these intervals bisected by water planes at levels

$$y_1, \; y_3, \; y_5, \; y_7 \ldots\ldots\ldots\ldots$$

and the corresponding offsets or x co-ordinates stated, then integration may be carried out using Simpson's 1 - 4 - 1 Rule. Since this rule implies fitting a parabolic arc to the three points of each interval, it is important that the offsets provided to define the shape of the ship should be chosen so that one of the boundaries of the 1 - 4 - 1 intervals, that is

$$y_o, \; y_2, \; y_4, \; y_6 \ldots\ldots\ldots\ldots$$

coincide with each discontinuity, point of contraflexure and the load water line. Having thus obtained the immersed "volume" of each section and, on a volumetric basis the righting moment, these can be integrated along the length of the ship to give its volumetric displacement and volumetric righting moment respectively. The pitching moment can similarly be found by integrating

$$\delta M_p = z \quad \delta v$$

As before, this integration may be carried out using Simpson's 1 - 4 - 1 Rule.

Since it is not practical to use a very large number of co-ordinate sets to define the shape of the ship, cross-sections are taken at, say, six stations and at the mid-points of the intervals so formed, making eleven stations in all. The programme in its final form makes provision for up to nine major intervals which are further bisected. The major intervals need not be of the same length. Boundaries of the major intervals, but not the mid points, should be arranged to coincide with any discontinuities. Cross-sections taken at each of the stations may be adequately described by six 1 - 4 - 1 intervals, which is to say thirteen offsets, and such provision is made in the programme. However such intervals are far too coarse to deal with the moving discontinuity caused by the water surface shifting, relative to the co-ordinate system, as the ship is heeled. In order to reduce such errors, the y intervals crossed by the water surface must be further subdivided into quitethin strips and the additional offsets or x co-ordinates obtained by parabolic interpolation. The fast access store in the computer is not large enough to contain these additional offsets, so they are obtained as required, used and then discarded.

The first step in the computation is the calculation of the standard volumetric displacement and the standard volumetric pitching moment. The latter, of course, defines the longitudinal centre of buoyancy which is matched by the longitudinal position of the centre of gravity. To achieve reasonable accuracy in this step, using Simpson's Rule, the load water line must be a boundary between major y intervals. When the ship is upright in still water, a continuous variation in heave will produce significant jumps in the computed value of displacement as the boundaries of the y intervals cross a water surface to which they are parallel. Once the ship is heeled, however, a reasonably continuous and accurate correspondence between fact and figure is achieved as account is taken of the varying slantwise immersed length of each boundary as it crosses the water surface.

The next step increases the angle of heel to 10 degrees and repeats the calculations. If the displacement and the pitching moment do not agree with the standard values, then heave and pitch are incremented in the right direction by rather arbitrary amounts and the calculations repeated again. If agreement of displacement and pitching moment with the standard values, within prescribed limits of accuracy, is still not achieved, then iteration proceeds according to Newton's method. That is to say, from the results of the last adjustment, the ratio of the increment in heave to the corresponding computed increment in displacement is obtained, and this is multiplied by the remaining error in displacement to determine the next adjustment in heave. A similar procedure is used to adjust the pitch, and the iterative process continues until either the desired degree of agreement is achieved or a certain number of iterations have taken place. The fact that there is some interaction between heave and pitching moment on the one hand, and pitch and displacement on the other, can lead to some false, and even ridiculous, values for the ratios of corresponding increments. Because of the risk of the programme bogging down at this stage, three provisions are made. Firstly the number of iterations is limited to seven and the computer proceeds to the next angle of heel even when neither displacement nor pitching moment approach their respective standard values. Secondly, when the last increment in displacement or pitching moment is very small, the arbitrary adjustment used to start the iteration is substituted. In such cases it is probable that the effect of a small adjustment has been overshadowed by the interaction. Thirdly, the results of all iterations are printed out providing a post mortem check on the behaviour of the programme. So far, experience in using the programme has indicated that these provisions are both necessary and desirable.

The third step increases the angle of heel to 20 degrees, but before repeating the operations of the last step, increments heave and pitch by the respective changes computed for the last 10 degree increase in the angle of heel. This linear extrapolation saves a lot of machine time by reducing the number of steps in the iterations.

The succeeding steps repeat the operations of the third step until the desired maximum angle of heel has been achieved. This maximum heeling angle can be readily preset in steps of 10 degrees up to 120 degrees.

The foregoing procedure is carried out firstly for still water, secondly for the ship hogging in a seaway and thirdly for the ship sagging. If when the machine stops, a black switch on the control panel is temporarily raised all the computations are repeated for the ship loaded down to increase the displacement by one eighth. A further operation of the black switch will cause the computer to deal with the ship running light at seven eights of the standard displacement.

Using eleven stations and heeling the ship to 70 degrees for each of the nine combinations of sea and loading conditions, the machine time was 25 minutes.

The machine is programmed to print out six quantities after each iteration. In order these are the sine of the angle of heel and the volumetric righting moment, the sine of the angle of pitch and the volumetric pitching moment, the heave and the volumetric displacement. As a rule only the angle of heel and the righting moment following the final iterations are plotted, but the other figures are useful for monitoring the programme, If they were suppressed, the machine time could be reduced by 10 or perhaps 20 percent, but it has not been thought wise to do so.

PROGRAMMING TECHNIQUE

The details of the order code used are peculiar to Silliac and will not be discussed here. The regular handbook contains all this information for the use of those who intend to construct programmes. However some general comments may be of interest.

There is no point in using an automatic computer unless the solution of the problem involves some sequence of operations which is repeated many times, perhaps with systematic variations. This is because a once-through sequence could be carried out as quickly on an ordinary office desk computer as the data could be prepared and punched on teleprinter tape for the automatic computer. The problem of ship stability does, however, involve three integrations through the immersed volume at every step; and the basic calculation of the buoyancy and moments of the elementary strips is repeated to the order of 100,000 times. This indicates not only that the automatic computer is the appropriate machine to use, but also that every effort must be made to reduce the running time of the inner loop which is the repeated sequence of orders concerned with the above-mentioned basic calculation. The logical design of Silliac is such that multiplication and division each require 600 microseconds of machine time compared with 50 microseconds or less for most other operations. Therefore, as far as possible, multiplication and division are carried out before entering or after leaving the inner loop. Often shifts of the register may be substituted since, in binary arithmetic, a left shift is equivalent to multiplication by two and a right shift to division by two. Each shift requires only 17 microseconds. The coefficients in Simpson's Rule are powers of two and subdivision of major intervals for integration maybe carried out in powers of one half.

The next most important procedure for reducing running time is the use of filters to avoid unnecessary computations. For example, when the boundaries of a major y interval coincide, such as when traversing a flat deck or when provision for an extra station is not used, a filter causes the unnecessary computations to be bypassed. Likewise, when a y interval is not crossed by the actual water line, being either completely immersed or completely clear of the water, it is not necessary to subdivide the y intervals for integration. Again a filter avoids the unnecessary computation. As mentioned earlier, the water line represents a moving discontinuity as the ship is heeled and cannot be properly handled by Simpson's or any other integration rule; therefore the error is minimised by reducing the width of the integration intervals. In this programme the major y intervals are subdivided into 16 minor intervals before applying Simpson's Rule. This is shown in figure 7.

Silliac, like most other electronic computers, uses fixed point binary arithmetic and requires that all numbers should be less than plus one and greater than minus one. Therefore all data must be scaled down for input and appropriately scaled up on output. If ships ranging in length from ten to one thousand feet are to be handled, that is a range of one hundred to one, this scaling must be made variable and, in fact, has been made automatic. The point is that the computations involve fourth powers of lengths as well as subdivision into small integration elements, and hence, if fixed scaling were used, the moments for a small craft would be sliding out the bottom of the registers. The stores and registers have a capacity equivalent to twelve decimal digits only.

The use of Simpson's Rule means that nearly half of the y co-ordinates bisect the interval between their immediate neighbours.

Although such co-ordinates are really redundant as information, it was considered better to feed them into the machine than to cause confusion by requiring selective omission. However the programme selects and overwrites these redundant data, using the stores as working space. Even with this economy, almost the whole capacity of the machine's fast access store is needed.

The data is prepared by punching on teleprinter tape the following:

a. The length of the ship.
b. The maximum angle of heel.
c. The 19 wave ordinates for the hogging condition.
d. The 19 wave ordinates for the sagging condition.
e. The 19 x 13 = 247 x co-ordinates.
f. The 19 x 13 = 247 y co-ordinates.
g. The 19 z co-ordinates.

The 19 stations need not all be used. However it must be remembered that

$$z_0 \quad , \quad z_2 \quad , \quad z_4 \quad , \ldots\ldots\ldots\ldots \; z_{18}$$

are the boundaries of the Simpson's 1-4-1 Rule intervals, which need not be equal, and

$$z_1 \quad , \quad z_3 \quad , \quad z_5 \quad , \ldots\ldots\ldots\ldots \; z_{17}$$

are the mid-points. For the usual 11 station layout, z_4 would be taken as station 0 and be negative, z_9 would be at the origin and represent station 5, while z_{14} would represent station 10 and be positive. For ships without appreciable overhang the spare co-ordinates would be entered as

$$z_0 = z_1 = z_2 = z_3 = z_4$$

and

$$z_{14} = z_{15} = z_{16} = z_{17} = z_{18}$$

so that the unused intervals would be computed as zeros. The x and y co-ordinates for the unused stations are all entered as zeros. The machine will automatically bypass most of the unnecessary calculations. Where there is appreciable overhang, additional stations must be used, and the provision for 19 stations was thought to be sufficient even for the extreme case of a deep keel sailing yacht. The order for presenting the y co-ordinates to the machine starts with the after station, whether used or not, and works from the bottom of the hull to the top of the superstructure before proceeding to the next station. The x co-ordinates are presented in the same order. The wave ordinates correspond to the z co-ordinates. The maximum angle of heel is presented as the number of ten degree increments required and has a maximum value of 12. The length of the ship is required to set the scaling factors and is therefore fed in first; it is not otherwise used in the computations. It is of the utmost importance that no item be omitted since the machine can only identify information by its position in the sequence. Unused spaces must be filled by zeros. Further, since the machine will cheerfully work on ridiculous data without protest, it is wise to punch two data tapes and feed them through the comparer which will stop at any discrepencies and so indicate punching errors. If two different operators can be employed, this check is so much more effective.

AN EXAMPLE.

The body plan of a tuna fishing vessel is shown in figure 8. The low freeboard aft and the high forecastle will be noted, and this combination points to considerable interaction between heeling and pitching, making the vessel an ideal example for the present

TUNA FISHING VESSEL.

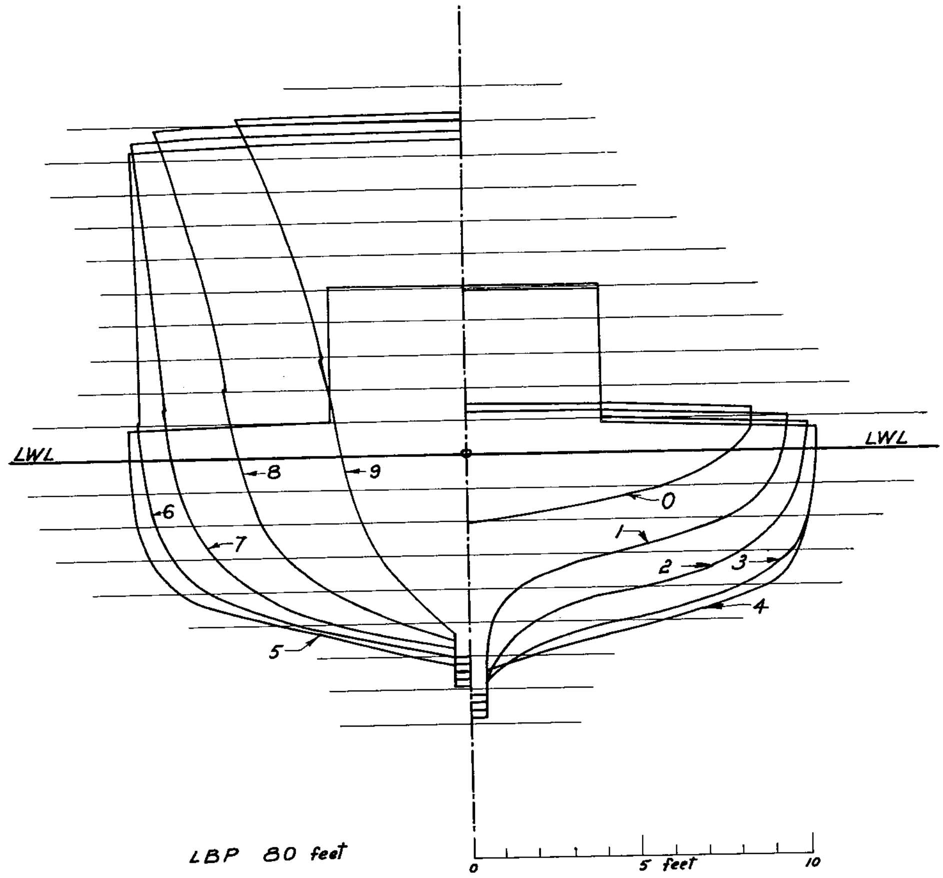
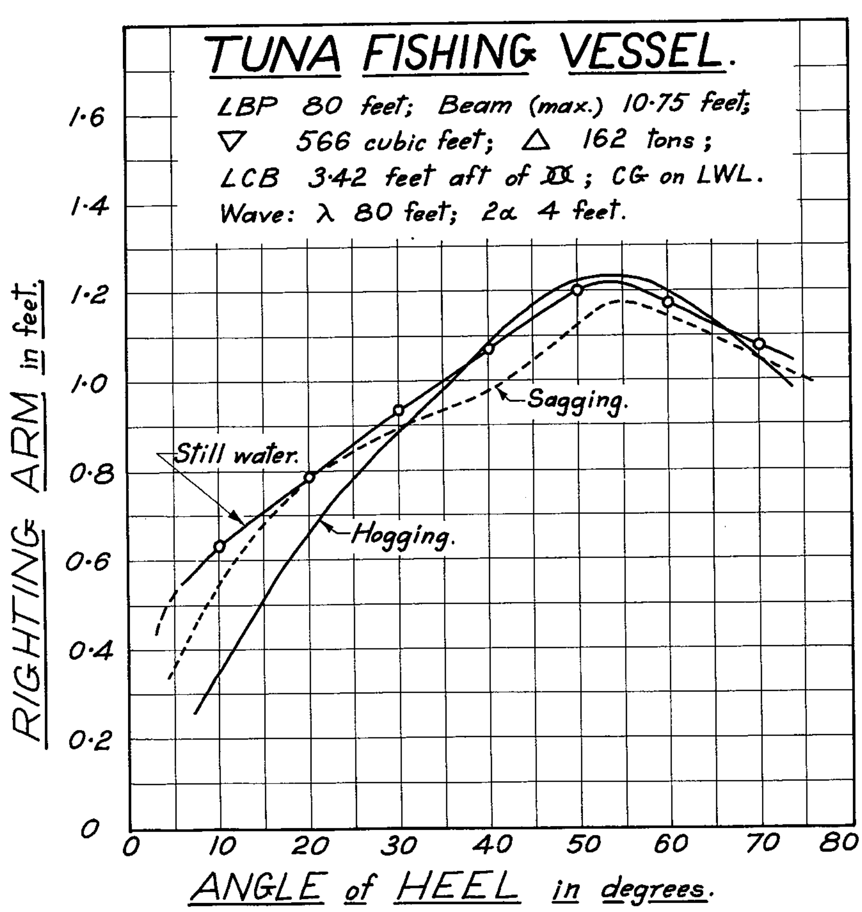


Figure 8.



"Silliac,"
Basser Computing Laboratory,
School of Physics,

R.F.H., 27-6-62.
Ship Model Test Tank,
Department of Mechanical Engineering,

The University of Sydney.

Figure 9.

SIMPLIFIED COMPUTER FLOW SHEET.

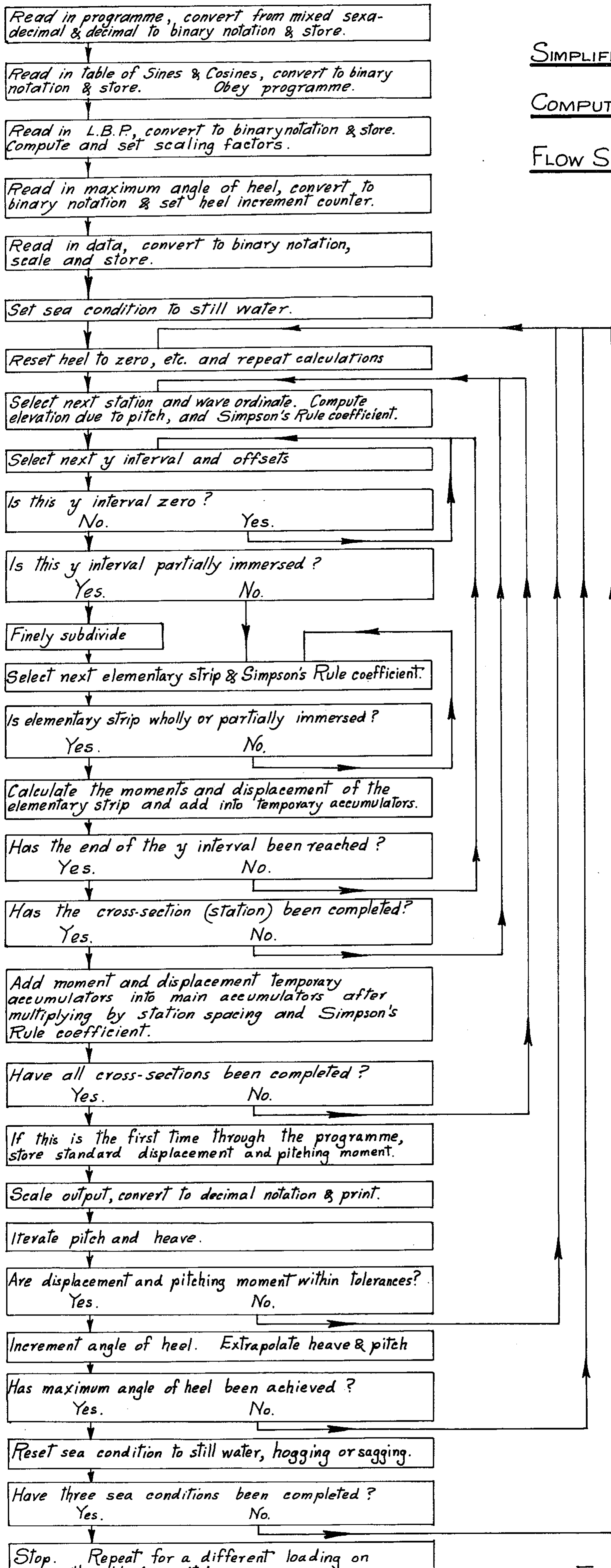


Figure 10.

purpose. The curves of righting arm against angle of heel are shown in figure 9 and reveal that the stability is seriously reduced in the hogging condition. In a practical application, of course, the position of the centre of gravity must be found, and if not at the load water line as has been assumed, then corrections to the computer output must be made. However this is a simple bit of arithmetic and was not considered to be worth incorporating in the programme. The curve for the hogging condition had previously been obtained using an Amsler integrator and very closely matched the corresponding curve in figure 9.

CONCLUSION.

It has been shown that the automatic computer can be used to great advantage in the calculation of the stability of a ship in a seaway. In fact it reduces the work involved to such an extent that it might be reasonably regarded as a routine design requirement. This is the kind of impact that the automatic computer has made in other fields, and it must inevitably alter the naval architect's thinking in relation to many problems which must now be solved by the opinion of an expert!

ACKNOWLEDGEMENTS.

The authors are grateful to the staff of the Adolf Basser Computing Laboratory at the University of Sydney, where the computations were carried out, and to the staff of the Hydrodynamics Laboratory where the model tests were made. This work is part of the programme of research and development being carried out by the Department of Mechanical Engineering. Thanks are due to the Professor of Machanical Engineering for permission to proceed with the project and for his interest in it. The authors appreciate the co-operation of the Maritime Services Board of New South Wales in making available the lines of the tuna fishing vessel together with the results of their stability calculations.

REFERENCES.

(1) K. C. Barnaby, "Basic Naval Architecture", Hutchinson, London, 3rd edition, 1960.

(2) J. R. Paulling, "The Transverse Stability of a Ship in a Longitudinal Seaway", Journal of Ship Research, Vol. 4, No. pp. 37-49, March, 1961. (Bibliography.)

(3) Private communication, Maritime Services Board of N.S.W.