NATIONAL SCHOOL SAILING ASSOCIATION

ROCK 'N ROLL

Curriculum Development Paper No 10

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ROCK 'N ROLL

A Project to Investigate Displacement and Stability

The object of this exercise is to examine the way in which a boat floats, what keeps her upright and what forces or conditions of lading tend to capsize her. The work can be done at a sophisticated mathematical level, in a simple experimental way or by a compromise between the two. For example, even if carried no further, it is worth knowing that with slack water in the hull, a quite small load on the gunwale will heel a boat over; the same load will have less effect if the boat is dry. The exact relationship between the centres of gravity and buoyancy in the two conditions could be found by experiment, by drawing or, working straight from the plans, by quite difficult mathematics. The project can therefore, prove equally valuable to ordinary school children or budding master mariners.

As the work progresses, a need will be found for some knowledge of the principles of mechanics and for some geometrical, algebraic and arithmetical skills. If these have been acquired previously, well and good; if not, thee is much to be said for arranging experience and practical work to cover the needs as they arise; at least in this way the necessary study will be purposeful and may thus help to involve the student in his own education.

The first requisite is a small area of calm water; a sink, a bath-tub, an old tank or even a crate lined with polythene sheet would serve . It is an advantage if a rectangular shape is used as this makes the measurement of volume at varying depths clearer and more easily understood. A good tank can be constructed of marine ply with fillets glued into the joints and a strong rail round the top. The tank, at working depth, is best filled to within 8 or 10 cms of tie top as this brings the surface to a level where it is easily seen and, if the water is dyed (perhaps with laundry blue) so much the better. There is much to be said for having the whole tank raised on some kind of stand to bring the edge to a: least waist height, thus avoiding a good deal of bending and peering. A strong ledge or rim of wood fitted round the top and overlapping the inside by 2 or 3 cms will prevent displacement experiments turning into swamp tests and will also provide elbow room for young experimenters.

The second need is for a boat to float in the tank . This should be made on the "bread and butter" principle and the layers should be clamped and not glued together so that the water-planes can be studied separately. Size is only of importance in that, as usual with experimental work, the bigger the better. Indeed, if it is large enough to make an appreciable difference to the level of water in the tank as ballast is added, there is much gained and, in that case, a volume scale can be fitted inside the tank and calibrated by adding a couple of litres of water at a time to facilitate measurements of displacement.

Probably the best size of model is about 20 cms less in length and width than the tank itself. Large models, however, are costly in raw materials and difficult to construct; anything much over a metre in length would present difficulties; anything under half a metre would make for inaccurate experimentation . Probably the best shape for a first model would be a "sharpie", with a flat bottom, flat sides with an overhang of about 1/4 and a transom stern raking aft at the same angle. This will, of course, produce a raked stem also. A length/beam ratio of 2/1 will provide a nice stable hull needing little if any ballast to float upright, though some weight aft may be needed to get her on even keel. A good material for construction would be 10 mil. marine ply or, alternatively, double layers of 5 mil.

ply glued together, thus making each water-plane exactly 1 cm. thick. If the model is a large one, the top and bottom layers are better made in double thickness to provide strength as they have to take the strain of the bolts which hold the whole thing together. (See Fig. 1)

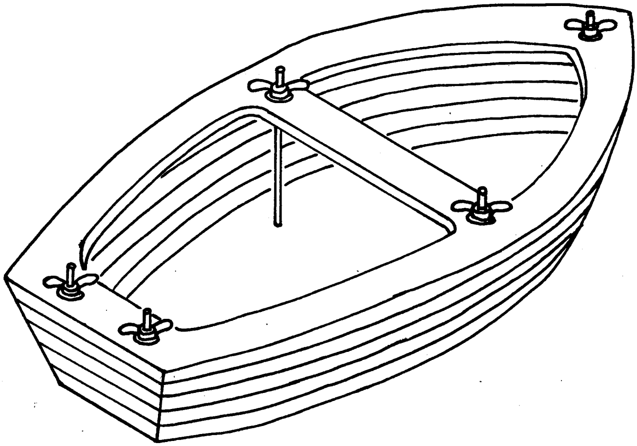
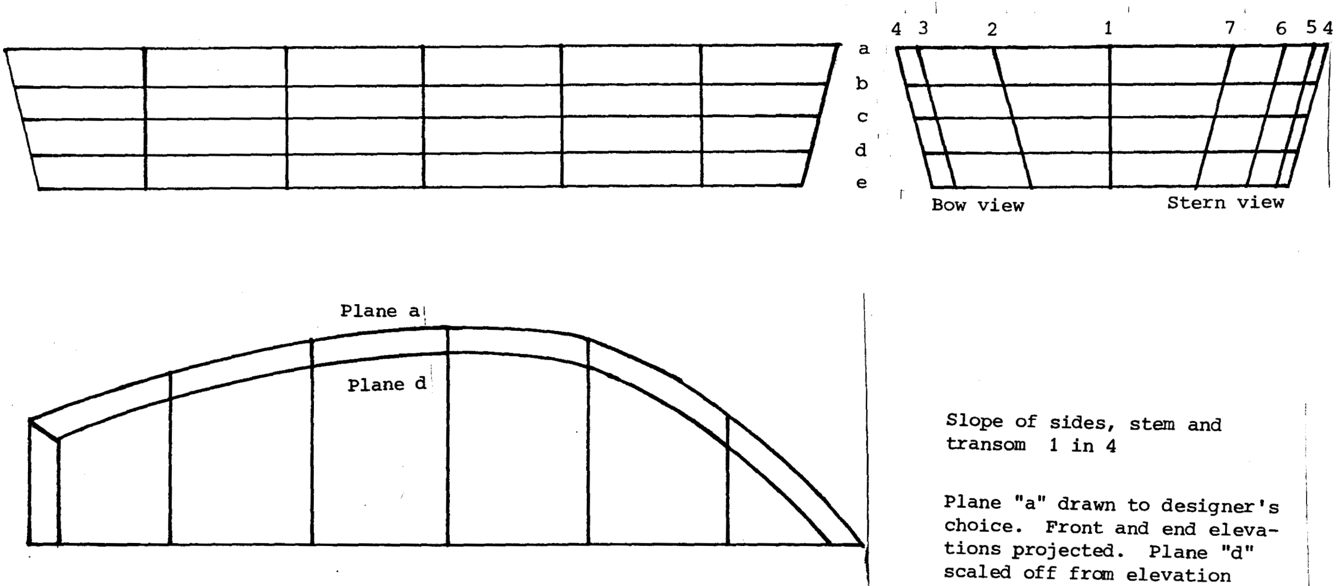


Fig. 1

The first step in manufacture is, as usual, to make a full scale set of drawings. With a "slab-sided" craft of this sort, this is not difficult. (See Fig. 2). The water-planes are then pricked through to the wood, cut out and, before proceeding further, cramped together to ensure that all is well. A hull thickness of a couple of centimetres can be left by marking this distance in from the edge with a pencil gauge and then cutting out each layer with a jig-saw. The bottom layer is, of course, left intact and the top layer should not be cut out until it has been decided how the bolts are to be fitted and this could, perhaps, best be decided after some experiments with "G" cramps. When the layers have been finally cut out and the whole thing bolted together, each water-plane should be pencilled round



Slope of sides, stem and transom 1 in 4

Plane "a" drawn to designer's choice. Front and end elevations projected. Plane "d" scaled off from elevation

Fig.2

on to the next above it and the bolts removed. Half a dozen short copper nails can then be driven through each layer to register into holes drilled in the next layer above so that the model will always fit together correctly. Finally the model should be bolted together again and the "steps" on the outside planed off, the angle being checked with a sliding bevel as the work proceeds. It is a useful trick to take a light shaving off each outside arris to leave "V"-shaped furrows along the whole length of the water-plane and these could later be picked out in colour. It is as well to finish all parts with paint or varnish and, when all is ready, to caulk the seams with scotch tape. This makes it unnecessary to screw the bolts up tightly and thus obviates the risk of distortion.

A useful accessory is a light mast of dowel rod, stepped through the thwart into a small block glued to the bottom . If the masthead be fitted with a "cap" extending clear of the thwart, a plumb-bob can be hung from it to measure angles of heel against a scale of either tangents or degrees. There is much to be said for having the plumb line an exact multiple of 10 as this saves a good deal of computation. (See Fig. 3).

Ballast could be made of anything; bags of sand, ordinary brass weights, lumps of rock or pre-cast cement blocks; in all probability, the most suitable material is plasticine. This can be moulded to a regular size and thickness, labelled and wrapped in cellophane, so easing the task of finding its centre of gravity.

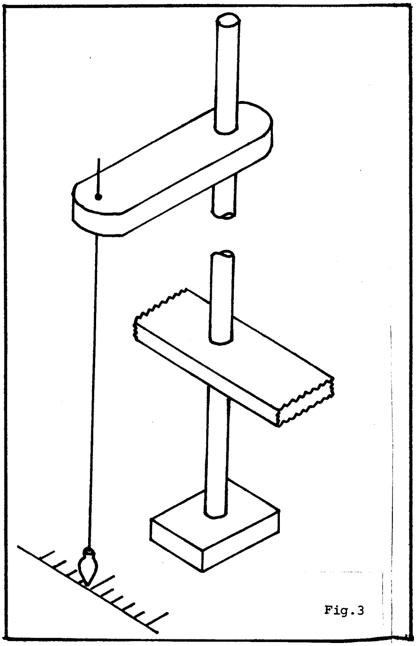


Fig.3

After launching the model with due ceremony, she must have her permanent ballast fitted to get her upright and on an even keel. A few scraps of lead nailed into the bottom should do the trick. After this she should be taken out of the water, weighed and her weight compared with the displacement shown on the tank's capacity scale . The hull might then have painted upon it the legend "Eureka. Light Displacement: xyz kilos".

A curve of displacement and of kilos per centimetre immersion (see Fig. 4) could then be constructed by experiment and compared with similar curves obtained by separating the layers, tracing round them on to squared paper , computing their areas and volumes and then converting into weight of water displaced . (It is here that the superiority of the S . I . system of measurement displays itself). The method suits different levels of ability since the least able can count squares while the mathematically more competent can apply Simpson's rules.

Another experiment worth undertaking is to add a few kilos of kitchen salt to the tank water to raise its specific gravity and it should not be too difficult to construct an hydrometer from a milk straw and plasticine for testing this. A fresh curve of displacement will show the reasons for at least two of the lines in a Plimsoll mark.

Having discovered something about displacement, stability is worth investigating. A load kept on the bottom might be steadily increased to deepen the draft, layer by layer and the angle of heel noted when a fixed weight is placed on the outer end of the thwart. This experiment might be followed by raising the centre of gravity of the load, resting the ballast on laths laid across the steps inside the hull, to see what effect this has upon the angle of heel. Similar experiments could be made by approaching the problem from the other end, as it were, ie., by keeping a fixed amount of ballast and increasing the heeling load until one gunwale is nearly under water. Again this could be repeated with raised ballast and therefore a higher centre of gravity. A small amount of water could be put into the bottom to match a quantity of ballastlremoved and the effect of slack water could be studied with some profit.

Other simple experiments worth conducting have to do with the way a vessel rolls. After loading varying amounts of ballast at different levels, the boat could be heeled over by hand to some pre-determined angle and then released . By timing the swinging mast for, say, 20 seconds with a stop-watch, the period of roll can be obtained. Many people are surprised to find that the more ballast there is low down in the hull, the more heavily the ship rolls and that, conversely, "The higher' the fewer". As in much else compromise is needed: great stability is only obtained at a price and the price is violent, motion.

It may well be that students will wish to pursue their studies to a greater degree of precision and will therefore want to develop more searching and accurate techniques. In this case, the next step would be to locate the centre of gravity of the model. Again this problem could be studied by experimental or mathematical methods, preferably by both. The hull could be balanced upside down on a point to mark the position for drilling a hole and inserting a vertical length of dowel rod, the top of which could be stayed to the sides with fine wire.1 The hull could then be turned on its side and balanced with the dowel resting on a knife-edge to locate the centre of gravity at a point in space part way up the rod. Alternatively, the layers can be separated, weighed and balanced on a knife-edge to find their individual centres of gravity

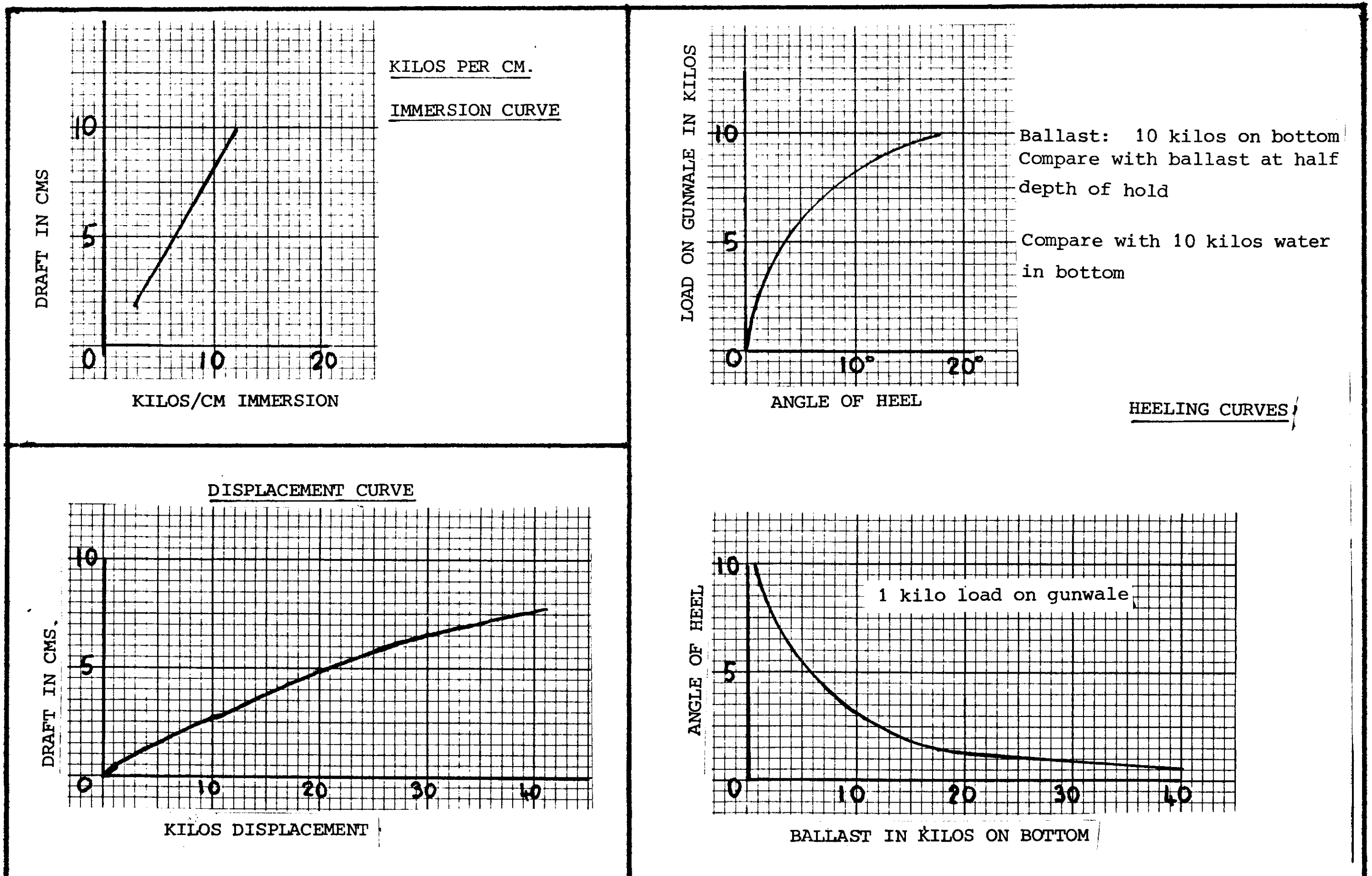

KILOS PER CM.
IMMERSION CURVE
DRAFT IN CMS
KILOS/CM IMMERSION
0
5
10
10
20
Ballast: 10 kilos on bottom
Compare with ballast at half depth of hold
Compare with 10 kilos water in bottom
LOAD ON GUNWALE IN KILOS
ANGLE OF HEEL
10°
20°
HEELING CURVES
DISPLACEMENT CURVE
DRAFT IN CMS.
KILOS DISPLACEMENT
30
40
1 kilo load on gunwale
ANGLE OF HEEL
BALLAST IN KILOS ON BOTTOM

Fig. 4

which could be assumed to be at half the depth of each layer. Moments could then be computed layer by layer, thus: Assume that the bottom layer weighs1000gms and the next one above it (being hollow) only 100 gms also assume that the bottom layer is 2 cms thick while the next is only 1 cm thick. Their centres of gravity would therefore be 1.5 cms apart.

Let x = the distance of the centre of gravity of the bottom layer from the common centre of gravity.

Let y = the distance of the centre of gravity of the second layer from the same common centre.

then x + y = 1.5 cms (the distance between both centres)

1000x = 100y (since the moments about the common centre must balance)

1000x = 100 (1.5-x)

1100x = 150

x = 0.136 cms which, added to 1.0 cms gives 1.136 cms above base.

This computation could then be continued, layer by layer, raising the centre of gravity by successive steps and, after making a similar allowance for the bolts. its final position would be arrived at.

If this algebra is beyond the students, a practicable trick for finding the vertical height of the centre of gravity is to construct an histogram with the width of the columns representing the thickness of the layers and their area representing their weight. This can be cut out, any very long layers folded back on themselves and the vertical height of centre of gravity found by balancing the cut out on a knife-edge. Using this method, the bolts are allowed for by cutting separate strips of paper of the correct length and area and sticking them down across the columns.

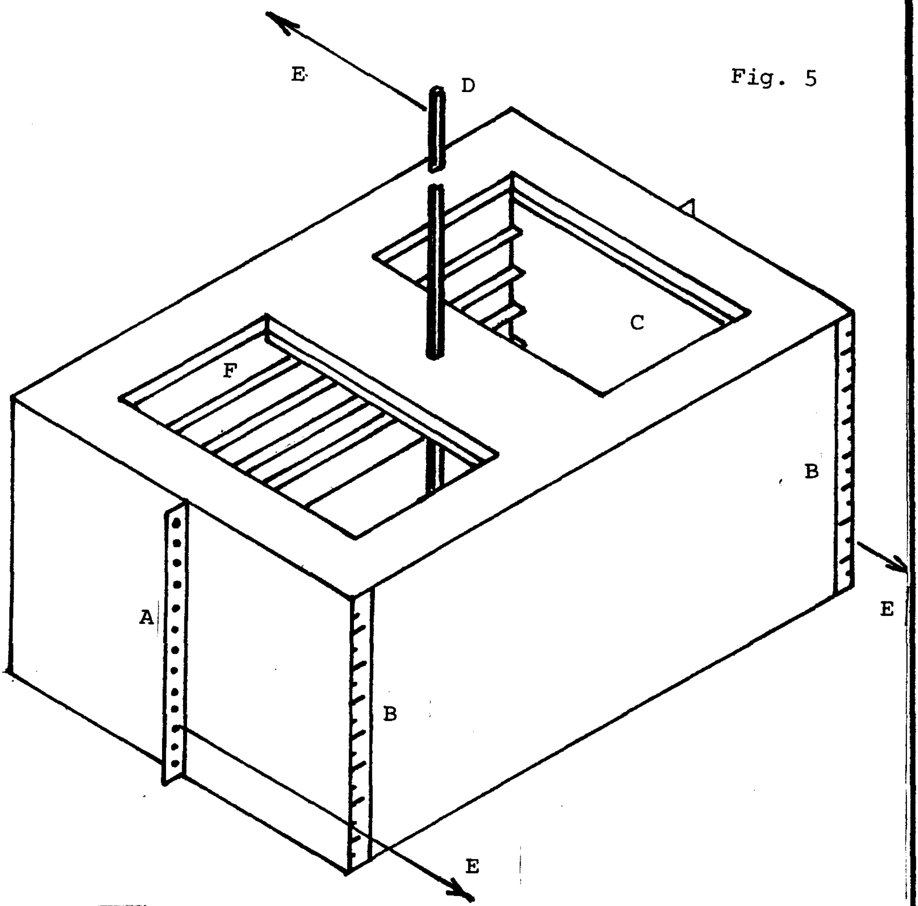
There is no reason why, given the density of the materials used, these calculations should not be made from the drawings instead of the model, arriving at the volume (and thence the weight) of each layer. This, after all, is what a naval architect has to do as he needs to have clear ideas about stability before his vessel is launched. There are of course, more elegant ways of solving the problem than counting squares , but the principle is the same.

Having found and marked the centre of gravity of the unladen hull , it is quite easy, by similar methods to compute its changes of position as ballast is added. If for no other reason, it now becomes apparent that there are advantages in having the load built up from standard sized blocks.

An interesting and valuable experiment, which might follow on these discoveries , would be to examine more closely the effects of off-centre loading. The new centres of gravity (shifted to one side by a weight on the gunwale) could be found as before and the resulting angle of heel measured. Since the upward pressure of the displaced water must exactly balance the downward thrust of the hull and cargo , the centre of buoyancy begins to be located; it will be directly beneath the new centre of gravity, and a scale drawing will show this clearly.

If more searching investigations are to be undertaken however, it is probably best to make additional models in sheet metal or plastic (See Fig. 5). In these matters where one is dealing with three dimensions, the curved shapes of the immersed parts of a boat-shaped hull present difficulties; those of a rectangular box resolve themselves into fairly simple wedges and rectilinear solids. It is better, therefore, to consider these models as the midship sections of flat bottomed and straight sided ships. Proportions are not very important, though there are advantages in having at least two modeLs with the same volume but with widely differing depth/beam ratios, as these will bring out important considerations in design for stability.

Fig. 5



A. Meccano
B. Draft scales
C. Hatchways
D. Mast
E. Heeling couple
F. Ballast brackets

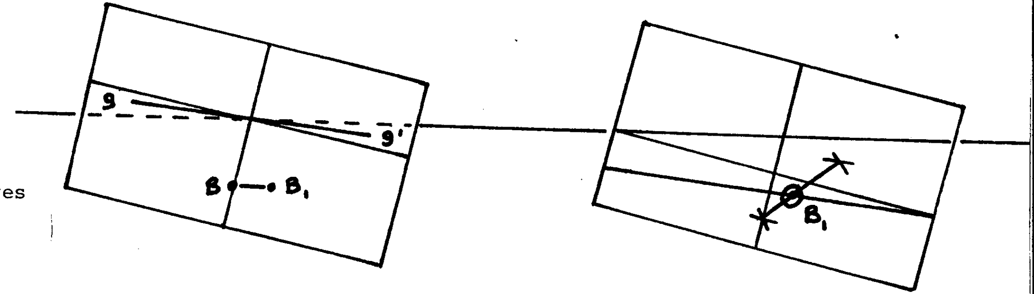
When making these models, it is useful to include four plastic rulers stuck on to the four corners as draft scales, a strip of meccano fitted vertically down the centre line of each end for "moorings", some internal brackets for resting ballast laths on, the usual mast and plumb line and hatchways for access to the hold.

The waste removed in making these last should be fixed under the deck to keep the centre of gravity at the geometrical centre of the hull; the mast may also need some small weight at its heel for the same reason.

Experiments in heeling have, so far, been done by displacing the centre of gravity and therefore the whole balance of the model, to produce a state of internal equilibrium. The next step is to heel the model over with external forces and without disturbing the balance so that it may be possible to study the righting forces and to discover how they originate . Mooring lines can be attached to the centre line fore and aft and made fast at the same level on the side of the tank. A light spring balance or pulley and weights can then be applied to the mast head so producing a couple to heel the model over. A curve can now be constructed graphing the heeling moments against the angle of heel. Since at any given angle, the model is stable, there must be a righting moment exactly balancing the heeling moment; this can only be the total weight of the hull multiplied by the distance between its centre of gravity and some point upon which the model may be thought of as resting. An hypothesis worth investigating is that this "centre of buoyancy" is at the centre of gravity of the immersed part of the hull. There are several methods of arriving at this last point, two of which are suggested in (Fig. 6).

Working from drawings, the length of the righting lever G. Z. (See Fig. 7) can be found for the several angles of heel previously investigated and the moment WxGZ, can be computed and graphed to compare with the moments arrived at experimentally. The point M in Fig. 7 is known as the metacentre and the distance GM as the metacentric height. As it is possible to arrive at this distance by experimental methods in a full sized

Fig. 6



gg // BB

g and g are C of G of wedges

$$BB = \frac{\text{Area of wedge x gg}}{\text{Displacement}}$$

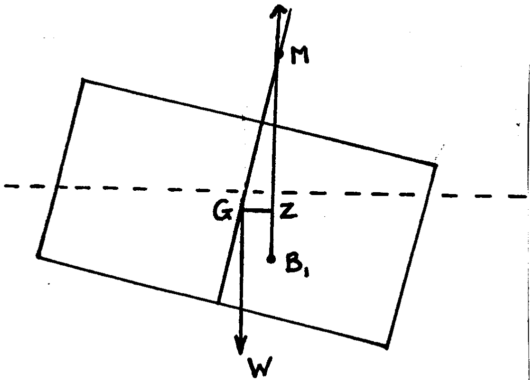


Fig. 7

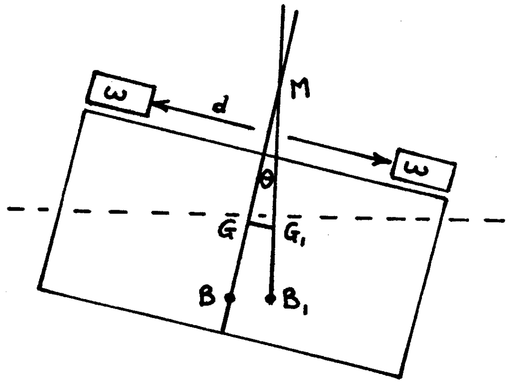


Fig. 8

ship, its connection with the righting lever is worth recording:

GM = GZ Sine angle of heel.

A graph of righting moments for all angles of heel (up to capsize point) is the ultimate aim of these studies and will show the angle at which, for example, a vessel will carry the most sail, the point beyond which even a reduced force will result in a capsize. Further, since the work done by a couple in heeling a boat over, is the product of its moment and the angle in radians through which it moves and, as the area of any element in a curve of righting moments is the product of such a moment and such an angle, the area contained between any two ordinates represents numerically the work done in heeling the vessel over from one angle to another. This suggests further work with sail areas, centres of pressure and lateral resistance, wind force and similar matters.

In any vessel, however large, the distance GM can be found by the inclining experiment so long as it is limited to small angles of heel (up to 5 or 6° usually). Here, a small weight (See Fig. 8) is set on one side of the deck and the vessel trimmed upright. The weight is then moved across the deck and its effect upon the centre of gravity computed ($GG' = {}^{dw}/_{w}$). The angle of heel (0) is measured and thence GM computed by the formula given above. Since the position of B' is a matter of geometry, it can be found by drawing as can the metacentre which, at small angles of heel, lies immediately above it on the centre line of the vessel. Hence the true position of the centre of gravity is found, even for a vessel of complex shape whose detailed lading is unknown though the total displacement is available from previously constructed curves.

For students who have pursued their studies this far, there is a case for repeating the experiments with slack water in the bottom, this time with the object of locating the "virtual centre of gravity". This is an imaginary point on the centre line above the real centre of gravity at which the total weight of hull and freely moving water may be thought of as concentrated . It is, perhaps surprisingly, more affected by the area of free surface than by the weight of water itself. The theory to be tested is that the distance between the real and virtual centres of gravity is directly proportional to the moment of inertia of the free surface divided by the total volume of displacement.

In dealing with the underwater sections of curved hulls, the practical method is to calculate the areas of equidistant cross sections and to erect these as ordinates in a graph . The area of this curve of areas will represent the total volume under consideration. Similar dodges of cutting out cardboard cross sections, finding their centres of gravity with plumb lines and graphing their moments about the centre line of the hull will produce a curve of righting moments which can be used in much the same way to find the centre of buoyancy.

If much of this work with curved hulls is to be tackled, a planimeter is an invaluable tool and, with a little ingenuity, craft of all shapes and sizes can be measured up and their stability characteristics investigated.

Wherever possible, the experiments should be drawn upon to provide lessons in the management of real boats . Equally simple experiments can be devised to bring the lessons home. "Boys per inch immersion scales" can be constructed for a dinghy or a cutter; inclining experiments are as easily done as in the model and the effect of a raised centre of gravity is wonderfully demonstrated by loading a few bags of sand on the thwarts of a dinghy and then stepping on the gunwale. "Sit down before the next man gets aboard" is sound advice. The most dangerous times in a yachtsman's life are shown by the records to be those spent in his dinghy betwixt ship and shore; if these lessons on stability were really grasped fewer lives would be lost.

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