Stability of a Sailing Yacht Floating Upside-down

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ABSTRACT

With the recent trend of cruising yachts towards light displacement type we are having an increasing number of "turn turtle" capsizes. A yacht thus floating upside-down can be sometimes very stiff to remain inverted for an extended time, even about one hour as it once happened in real world. The case took place during Japan-Guam Race in 1991-92 causing a heavy loss of lives to stimulate Japan (smaller) Craft Inspection Organization, as a semi-governmental body, to launch a research project on the safety of sailing yachts at sea. This paper deals with a part of the result concerning the present subject.

A full-size stability experiment of a 25 foot cruiser/racer floating upside-down is first mentioned. Her conventional companion covering did little about stopping water, thus allowing rapid flooding. The yacht gradually lost her stability at inverted mode by flooding and finally re-capsized by herself to right up in about 10 minutes.

A hydrostatic analysis follows to investigate matters. How the stability range (stability vanishing angle) relates to the re-capsizing is discussed. A few suggestions on emergency tactics are also presented.

1. FULL- SIZE EXPERIMENT

1.1 Procedure and Results: A 25 foot cruiser/racer, YAMAHA Y-25 Mark II was employed to investigate what will happen after turn turtle capsize , her principal dimensions and rough drawings being shown in Figs.1 and 2. The mast, rigging and auxiliary motor were removed before the experiment but the total weight and centre of gravity position remained unchanged by means of compensation weights. Difference in rolling moment of inertia does not matter as long as the static behaviour is concerned. Basic furnishings below deck remained as it was.

The experiment was carried out in an indoor square basin at the University of Tokyo, Dept. Naval Architecture. The yacht was forced to turn turtle using a pair of slings pulled by a power-winch. A video-camera inside the cabin monitored and recorded flooding. Heel, trim and water level outside were recorded by an accelometer, shore-based cameras and manual reading.

The yacht had a usual weather-tight companionway with a horizontal slide-hatch and washboards. Speaking truth, watching through the monitor video the water flooding in there was just impressive; only 5 minutes after turning upside-down the water level inside the cabin was already approaching the companion sill (now the highest point of the opening). At this stage the air inside the cabin was still finding way out through the gap of washboard and flooding water was replacing the escaped air. Thus we should not have any illusion with the slide-hatch and washboard to stop water; the arrangement may work for green seas washing over but once it is immersed underwater continuously, it can not do much about preventing water from getting in.

Soon after the water level inside reached the companion sill, however, the rate of flooding began to ease. Provided that galley sink drain-cock and alike were all closed, now the air inside would scarcely find any way out. In other words, the air was trapped inside to prevent water from further getting in.

In case of three tries out of four, the water inside tended to shift bowward to cause an appreciable trim by the bow at this stage as indicated in Fig. 3. At the same time in this situation the metacentric height GM (of course at the inverted attitude) had already become *negative* , which in turn created a certain amount of steady heel in spite of no asymmetric solid weight aboard. This loss of stability came from the reduced water-plane and free-water effect of flooded water. The steady heel gradually increased as shown in the inset graph in Fig.3 and finally the yacht did re-capsize by herself and righted (Photos.1 through 4). The time spent from turning over to re-righting was 11min.20sec., 4min.50sec. and 9min.19sec. respectively for the three tries above-mentioned. Meanwhile in the real world the re-capsize would supposedly take place considerably earlier encouraged by any external disturbance. The weight of flooded water estimated from the displacement after re-righting was about 2.5 tons which was some 25% over the yacht's intact displacement but still within such an amount that average crew could readily bail out (cf. Fig.3., bottom).

Only one case out of four was somewhat different. In this case the flooded water apparently distributed itself evenly fore-and-aft for some reason and no appreciable trim was observed, as indicated in Fig.4. The reason for the difference is not very clear but the initial attitude given by turning-over operation might be related to. At any rate, in this case the yacht maintained her "turn turtle" position as long as 70 minutes after capsize, when we gave up to continue.

According to the inset graph in Fig.4, however, again in this particular case the heel angle began to gradually increase about 10 minutes after capsize in spite of no asymmetric solid weight aboard. It suggests presence of a negative GM also in this case due to the same cause as the other three and in real world external disturbance would force the yacht to re-capsize perhaps before very long.

1.2 Major Findings from the Experiment :

1. Once it is immersed underwater a usual companion cover composed of a slide-hatch and washboards can not do much about stopping water from getting in. In case of "turn turtle" capsize it is a matter of minutes before the flooded water inside reaches the companion sill which is now the highest point of the opening.

2. Stability of a yacht floating inverted can be quite stiff at the beginning but soon it will reduce to much extent affected by shrinking water-plane and the free-water effect of flooded water. In order to make it clear a quantitative hydrostatic study on a yacht floating upside down should be called upon.

3. Effect of trim by the bow on the loss of stability at the inverted mode is considerable. Most likely it comes from the fact that bow trim results in more shrinkage of water-plane and also that bow trim gives the companion opening a more chance to stay on the surface, which means more escaped air then more water in. Incidentally here is a possibly controversial tactics in case of turn turtle; shifting the crew weight to the forecastle may encourage an earlier recovery from total capsize.

2. HYDROSTATIC ANALYSIS

2.1 General Consideration: At the beginning stage of floating upside-down, the main gateway of flooding is normally the slide-hatch that is now the deepest point of companion opening and therefore exposed to the highest water pressure outside. At the same time air inside the cabin finds the way out through gaps around washboards to invite flooding.

Sooner or later water level inside reaches the companion sill that is now highest point of the opening. Air inside the cabin is then largely prevented from escaping but still now and then the sill may be awash *inside* the cabin, forced by the hull movement, each time allowing some more air to escape thus calling some more water in. At this stage the water level outside is already appreciably higher (nearer to the keel) than that of inside and the pressure difference is pushing the air inside to get out.

Finally the companion sill gets constantly immersed underwater inside the cabin and the air has no way out any more, of course assuming all the sea-cocks to be closed. A certain amount of air is now "trapped" inside the hull and the yacht has taken more or less a state of equilibrium.

Fig.5 illustrates this situation. Small arrows indicate the hydrostatic pressure. Interesting is the level difference between the outside and inside water. Denoting the level difference as ***h*** in metre, the static pressure on the inside surface is
~~**1025 *h*** kg/m^2 (in case of sea water)~~.

This pressure pushes up the trapped air, which in turn pushes up the hull bottom from inside. In fact this supports a major part of the yacht's weight, i.e., the intact displacement . The rest of the yacht's weight is supported by displacement of the part of the hull structure and interior furnishings that is totally underwater, i.e., below the inside water surface. Incidentally the above-mentioned major part of the yacht's weight is strictly equal to the displacement of the part of the hull body cut out by the two water-planes passing the outside and inside surfaces. In fact it is slightly different from the integrated pressure on the inside surface by the integrated static pressure on the outer surface of the shell.

In the meantime the static pressure on the inside surface compresses the trapped air but the induced pressure rise and volume shrinkage are within a few percent for existing size of sailing yachts. It creates a little more sinkage of the yacht but again it is within a few percent of a canoe body draft. Even less is trapped air volume change induced by heeling over, though it is theoretically not nil. This effect is thus considered negligible and trapped air is actually an incompressible fluid, so far as a sailing yacht is concerned. For larger ships, however, there may be different stories.

2.2 Initial Stability at Inverted Mode: Now let us deal with stability at inverted mode indicated by Fig.5. , taking account of the trapped air and flooded water.

First take the initial stability at very small angle of heel. Referring to Fig.6 and following the usual mathematical reduction of metacentric radius BM, we get

$$BM = (I_x - I_{xi}) / V \qquad \text{(Eq. 1)}$$

where $I_x = (2/3) \int_L y^3 \, dx$: 2nd moment of outside water-plane on WL_o (m^4)

$I_{xi} = (2/3) \int_L y_i^3 \, dx$: 2nd moment of inside water-plane on WL_I (m^4)

V : displacement volume of the yacht at upright condition (m^3)

$\int_L dx$ denotes an integration from bow to stern lengthwise. y and y_i are indicated in Fig.6.

The term$(-I_{xi}/V)$ represents nothing other than the well-known free-water effect but in this particular case, unlike the same effect caused by a small tank for example, it has a decisive effect on the initial stability at inverted mode; indeed it can result in total loss of stability to re-capsize the yacht to right up by herself. This is already touched upon in discussing the full-size experiment previously mentioned.

2.3 Stability at Inverted Mode with a Finite Angle of Heel: The real world is somewhat more complex, however. Problems to be considered are:

1. With a given volume of trapped air, in other words a given weight of flooded water at 180° inverted attitude, we need to determine a proper set of outside water- plane WL_o and inside one WL_I, i.e. , to know the sinkage and trim of the hull and also the level difference h of the two water-planes, with which the gravity, buoyancy and their moments take balance to each other.

2. When the yacht heels over to a certain angle, her vertical position(sinkage) and trim do generally change so that we have to re-define the two water-planes WL_o and WL_I to seek a new equilibrium.

3. When the yacht heels over, the inside water-plane often crosses to the inboard-side of the deck and the cockpit-well wall, which normally causes a drastic reduction in the inner second moment I_{xi}. In many cases an initial negative GM at 180

inverted mode does recover its positive value at a small angle of heel from 180 by this reason. This is clearly seen in Fig.8 by the behaviour of GZ around 180° heel.

All these problems need repeated iteration process which the computers today are most good at. The program we developed at the Osaka Prefectural University, Dept. Naval Architecture is to integrate hydrostatic pressure over all the hull surface underwater plus the inside water-plane WL_I as is illustrated in Fig.5. Through this program we can first obtain the sinkage, trim and level difference between the outer and inner water-planes, i.e. position of the two water-planes, at 180° inverted mode for a given hull configuration and a given volume of trapped air. Then the program provides the righting arm GZ for a given angle of heel, taking account of change in sinkage and trim .

Another program for the same purpose developed at the Ship Research Institute assumes flooded water as if it is enclosed inside the hull without flowing in/ out and then employs a normal procedure of obtaining the righting arm GZ, taking account of shift of flooded water and the trim and sinkage induced. In theory a slight amount of flooded water can flow in/out caused by pressure thence volume change of trapped air but in reality it is well negligible as is touched upon at the end of **2.1.** The former program can accommodate this trapped air dynamics and thus perhaps it is theoretically more strict, but in actual application the latter is equally powerful.

Figs.7 and 8 indicate the two typical results, one for 1/10 scale model of a 31ft .IOR-type racer and the other the yacht employed at the previous full-scale experiment. Incidentally Fig.7 employed the latter program and Fig.8, the former.

2.4 Major Findings: We have made a number of calculations using the said program to get major findings as follows:

1. .With increasing escaped air and more water flooded accordingly, the stability at inverted mode rapidly reduces. Among the two factors for the reduction already mentioned in 1.2-2, the free-water effect, represented by the term $(-\ I_{xi})$ in the Eq.1, seems to be dominant. In most cases the reduction will sooner or later bring about total loss of stability at inverted mode and the yacht will re-capsize by herself to right up. Crucial is how early the self-righting will happen and perhaps more importantly, how much water is taken in before the re-righting; the less the water taken in, the safer the situation after re-righting , at least from crew's psychological point of view, and also easier to bail out .

2. As a general trend, a yacht with a relatively small stability range (stability vanishing angle) has a large GM at inverted mode and therefore needs rather great amount of flooded water before losing that stiff stability inverted. On the contrary the greater stability range results in the earlier recovery with the less amount of flooding.

3. Safety consideration after the re-capsize caused by flooding may be not exactly in the scope of the present work but let us have a few words upon it as a related crucial subject. Referring to Fig.7, the greater the flooded water the smaller the righting arm GZ gets in the whole range of angle of heel but at the same time the stability range becomes the greater. Since a large stability range is the decisive ability to avoid capsize, a yacht containing a great amount of flooded water is presumably quite safe in spite of her very low righting arm GZ, contrary to the common belief. A capsizing model experiments carried out with the same model as Fig.7 seem to assure this reasoning. On the other hand we should bear in mind the danger of total swamping and eventual sinking in this concern.

CONCLUDING REMARKS

1. The main cause of self-righting of a yacht once has turned turtle is most likely loss of stability at inverted mode, which is induced by flooding through companionway. In particular this is almost certain for a yacht with wide beam and shallow canoe body, having stability range of less than about 130° .

2. Water/air-tight companion-cover may not be impossible by means of packing and tightening handles. It might be a good idea for a yacht with stability range of more than about 140° as such a yacht has a rare chance to stay upside-down for long even in intact condition, but beware, for a yacht with relatively small stability range it would be the best means of staying upside-down forever after turning turtle.

3. Trim by the bow at inverted mode seems to encourage re-capsizing thence self-righting. Worth considering is an emergency tactics of shifting crew to the forecastle after turn turtle, or even better if available, shifting water ballast to the bow.

4. The present work deals with the behaviour of a yacht floating inverted, particularly the process of losing stability to re-capsize on a *still water*. In the real world there is normally a considerable external disturbance to stimulate an inverted yacht to move around, therefore re-capsize to right up by herself may occur

somewhat before her stability at inverted mode is totally lost.

ACKNOWLEDGEMENT

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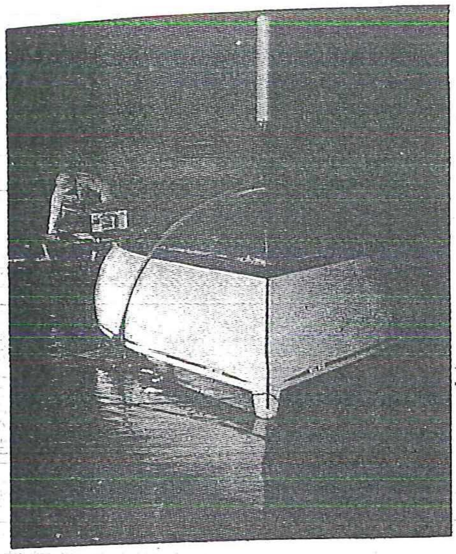
Photographs 1 through 4

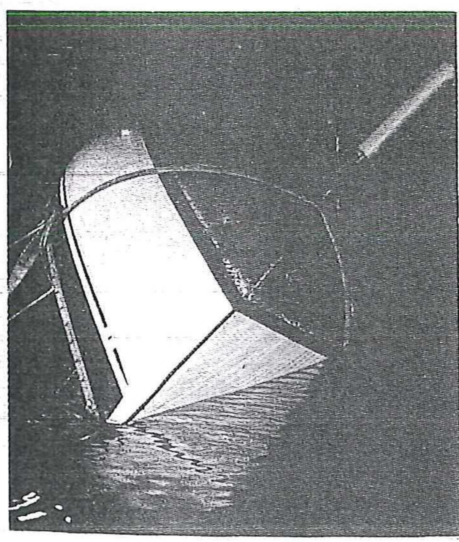
Full-scale Experiment on Inverted Stability

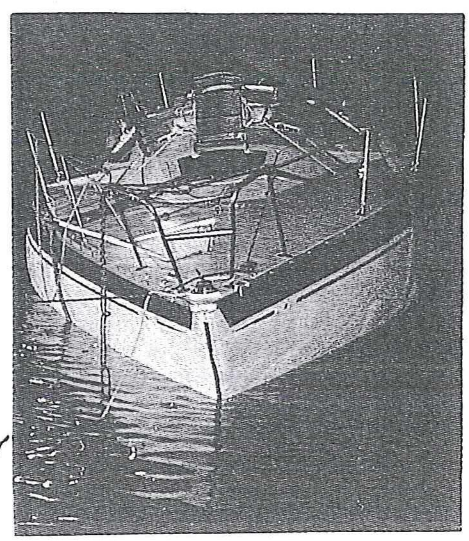


1. Just after turning-turtle
heel angle : 0

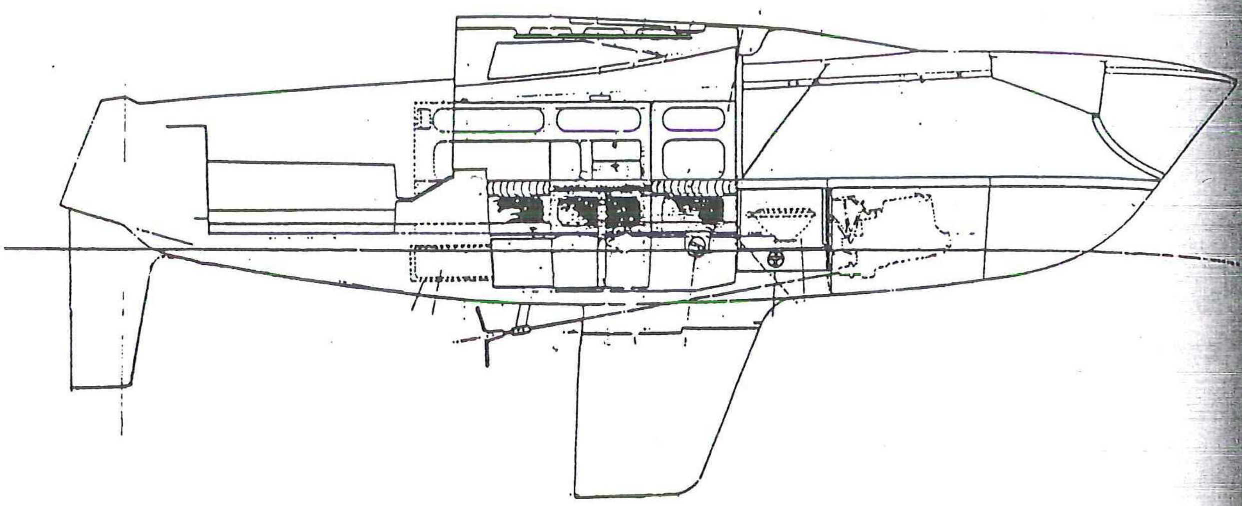
2. 8min.30sec. after
heel 15° ,uneasy attitude

3. 9min.15sec. after
re-capsizing by herself





4. 9min.19sec. after
now righted up



L_{OA}	: 7.60 m	Δ	: 1.95 ton	(test condition)
L_{DWL}	: 6.00 m	GM	: 0.86 m	(test condition)
B_{max}	: 2.80 m	$GM_{INVERTED}$	: 1.52 m	(test condition)

Fig.1 Arrangement Profile of Y-25 MarkII

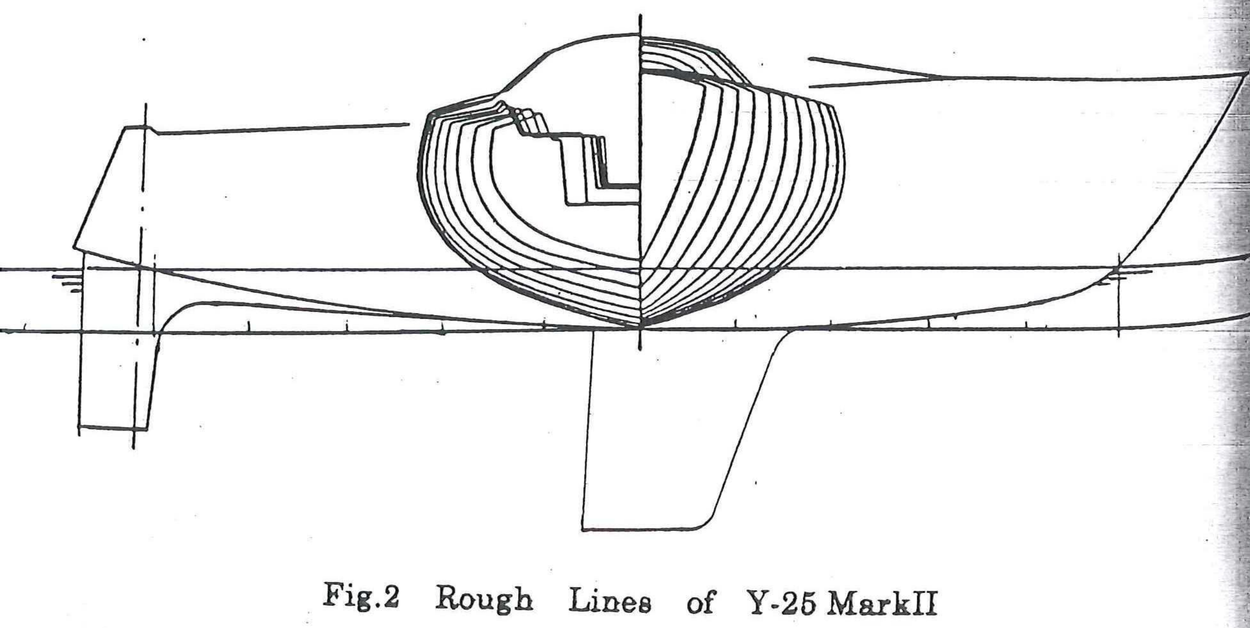


Fig.2 Rough Lines of Y-25 MarkII

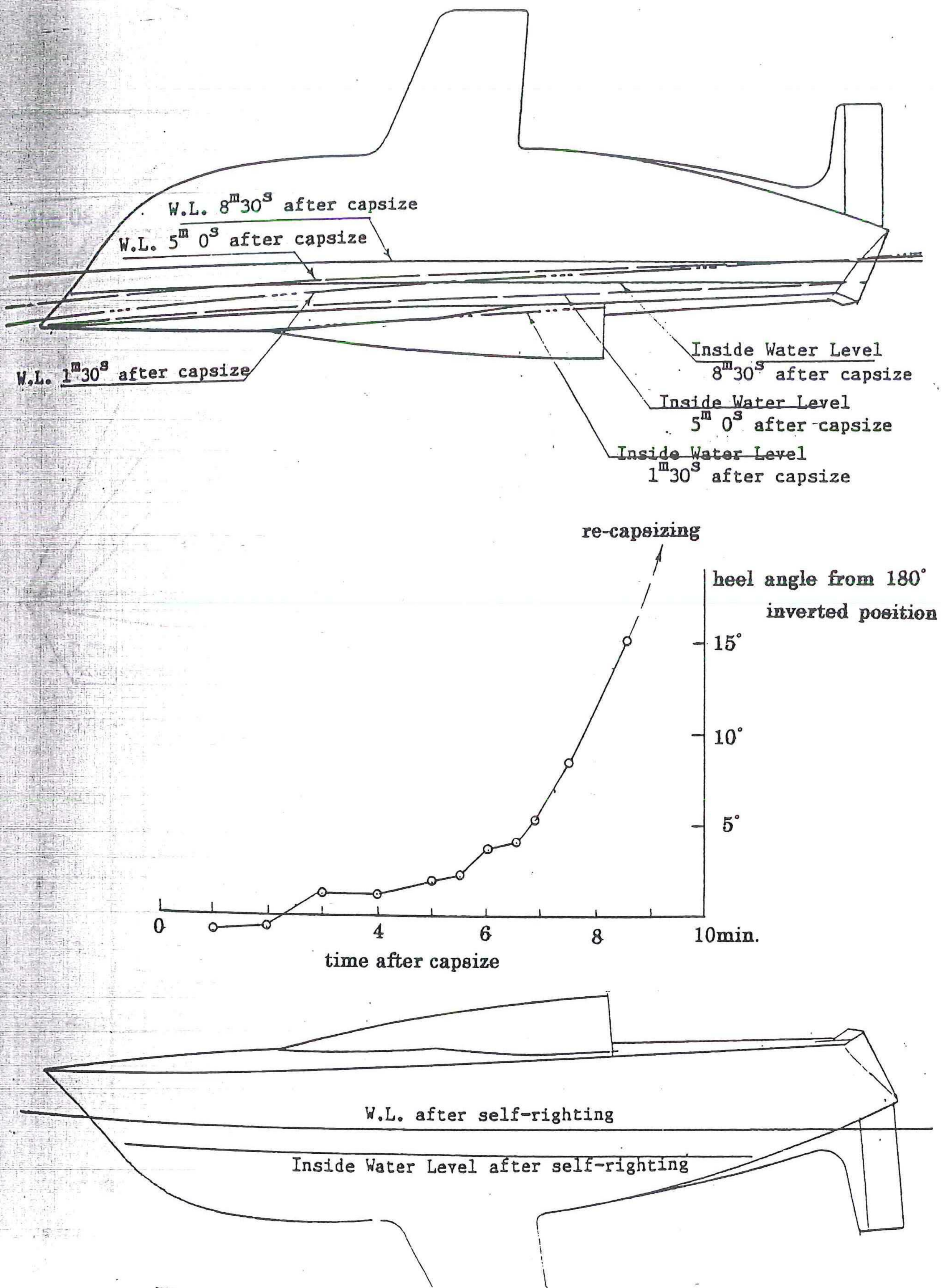


Fig.3 Full-scale Experiment of Inverted Stability, Test No.3.

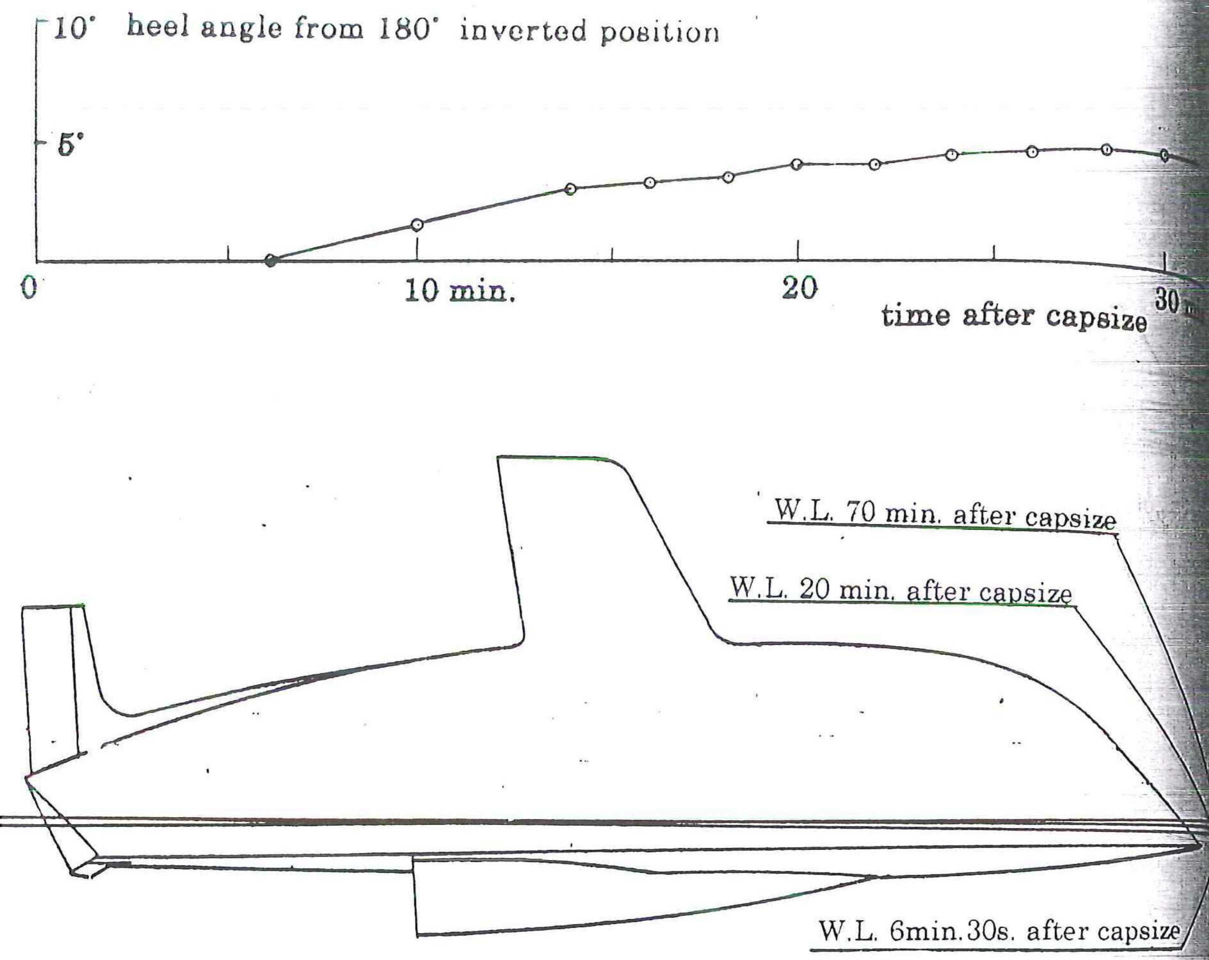


Fig. 4 Full-scale Experiment of Inverted Stability, Test No.4

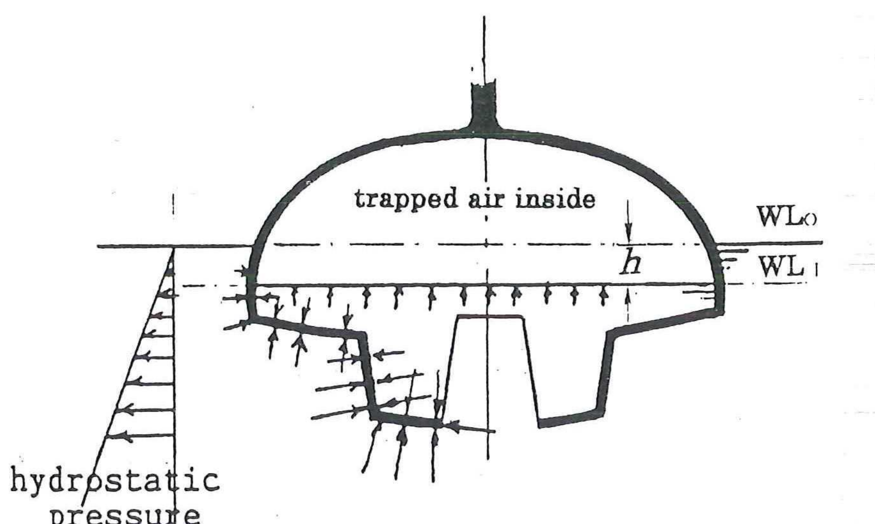


Fig.5 Hydrostatic Pressure Distribution when floating upside-down

Displacement volume enclosed by the two water-planes WL_0 and WL_1 and the shell surface supports most part of the yacht's weight.

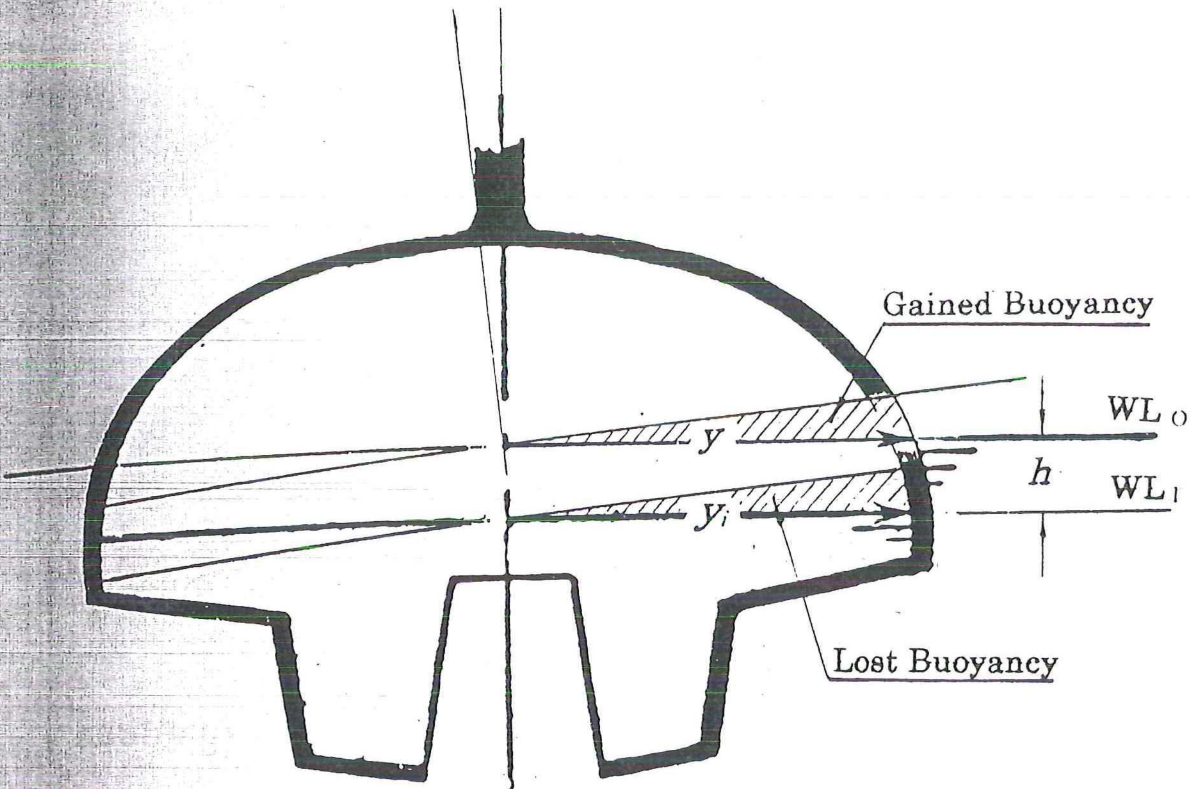


Fig.6 Effect of Flooded Water upon Inverted Stability; buoyancy gained on the outside water-plane is much cancelled by buoyancy lost on the inner water-plane

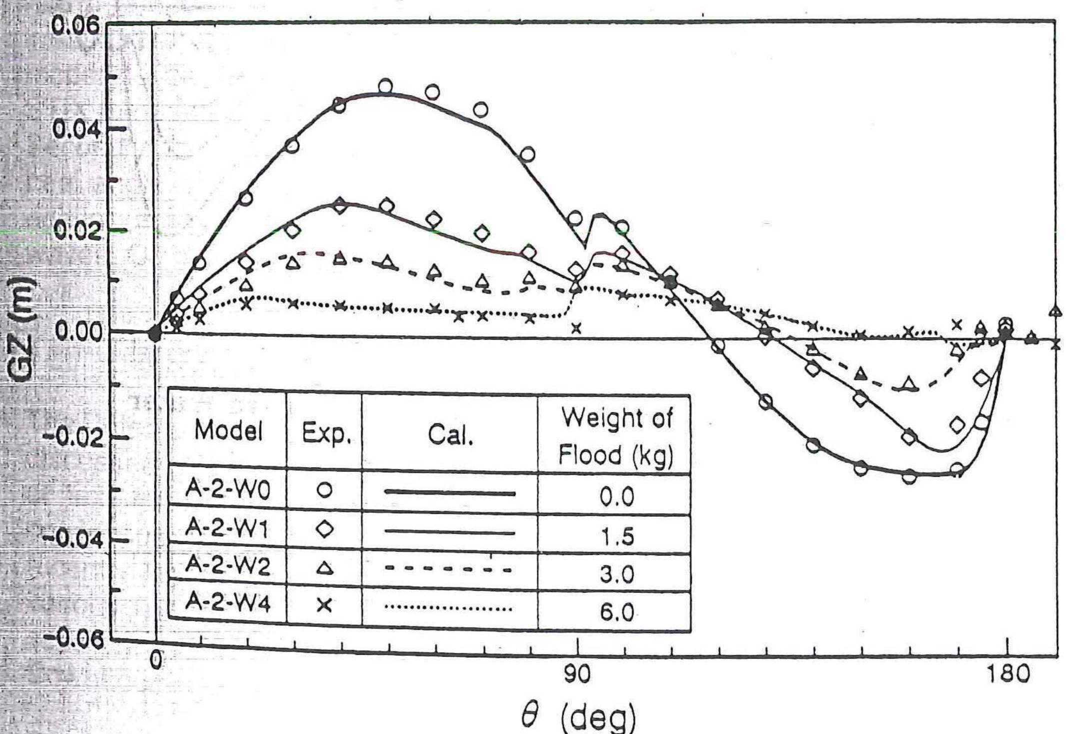


Fig.7 GZ Calculation with Experimental Data of 1/10-scale Model of an IOR Racer with Flooded Water (SRI/JCI Report 1944)

L_{OA} : 0.929 m B_{max} : 0.312 m △ : 3.03 kg(fresh water) GM : 0.088 m

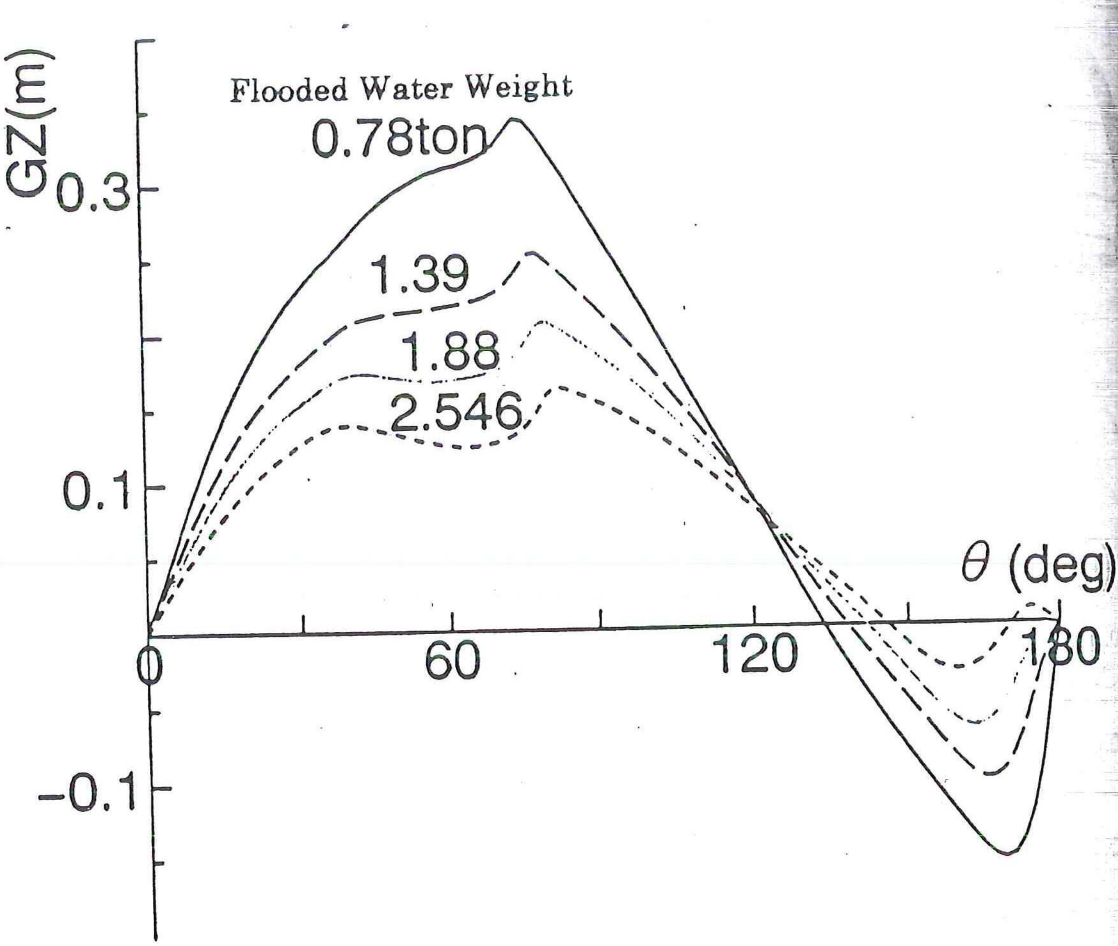


Fig. 8 G Z Calculation of Y-25 MarkII with Flooded Water (JCI Report 1994)

L_{OA}	: 7.60 m	Δ	: 1.95 ton	(test condition)
L_{DWL}	: 6.00 m	GM	: 0.86 m	(test condition)
B_{max}	: 2.80 m	$GM_{INVERTED}$	: 1.52 m	(test condition)