The International HISWA Symposium
on Yacht Design and Yacht Construction

Model Tests to Assess the Manoeuvring of Planing Craft

Barry Deakin
Wolfson Unit M.T.I.A., University of Southampton

Abstract

This paper outlines the qualities which are required for good manoeuvring and control of high speed craft, and some of the design parameters which influence them. It describes a system of simple tests which can be conducted on radio controlled models, for design projects with a modest budget, to highlight potential control problems or to define boundaries of specific design parameters.

The paper is illustrated with data from recent commercial testing contracts.

Background

Planing craft designs have evolved and developed and, in general, good behaviour is assured with new designs deviating little from previous successful boats. Despite this, most people in the industry will have a tale to tell of a craft with an undesirable, or even dangerous, handling characteristic.

While more craft are being operated at high speeds, and innovative designs are being produced for specialised operational requirements, the incidence of craft with manoeuvring problems is not diminishing.

The designer of a planing craft will influence the directional stability and control by his choice of hull form, appendage design, and transverse stability. Unfortunately there are few reliable formulae or published data on which he can base a prediction of these qualities.

Model testing offers a means of assessing a proposed design prior to production, but conventional ship model testing techniques require detailed and accurate model hulls and appendages, and precise test execution. They have developed to provide data for assessing and comparing standard manoeuvring characteristics in some detail. Justifiably these are seen as prohibitively expensive for the typical planing craft budget and, being developed for large slow ships, may not highlight the problem.

The Wolfson Unit specialises in testing small models of fast craft, and has many years of experience in the investigation of their manoeuvring through towing tank and simple free running model tests. Recent projects have included studies of the control of planing craft at an early stage of their design, when the test results might have a strong influence on some parameters.

One of the recent contracts concerned a 15 metre lifeboat for the Royal National Lifeboat Institution, with a design speed of 25 knots. Eight hull versions were tested at a scale of 1:10, some with twin water jets and others with twin propellers in tunnels. The boat was intended for slipway launching, and the practical constraints on the bilge keel and central keel arrangement had significant implications for the manoeuvring. The other contract was for a 16 metre pilot boat to be built by Halmatic Ltd. It had a design speed of 32 knots, with propulsion by three water jets. The decision to incorporate a central jet precluded the use of a conventional central skeg, and therefore had a large influence on the manoeuvring characteristics. This boat was also tested at a scale of 1:10.

The operational requirements of both craft include good manoeuvring at high speed and in severe seastates, so the study of handling was given a high priority. With a large number of test configurations to compare however, a simple and low cost modelling and test procedure was required, which would address the concerns of the designers and help to define the boundaries within which the design could develop.

Manoeuvring qualities

There are a number of interrelated characteristics which are desirable attributes for most craft:

1. Good directional stability. This quality will ensure that the boat will hold a steady course in the absence of external forces, and will respond positively to helm angle changes. A boat with negative directional stability may continue to turn after the rudders have been put amidships.

2. Good manoeuvrability at speed. The boat should be able to manoeuvre within a reasonable turning circle. Unfortunately manoeuvrability and directional stability are opposing characteristics, and an improvement in one is usually at the cost of the other.

3. Good manoeuvrability when idling. This is usually achieved through independent port and starboard throttle controls, but may be influenced by design.

4. Good response to the helm. The boat should respond with a significant heading change following the application of helm. This should not be confused with positive directional stability, for example a boat with high directional stability and small rudders will be difficult to turn.

5. Moderate heel in a turn. Excessive heel in a turn, particularly if it is outward, gives the crew a feeling of insecurity, and frequently leads to other control problems.

6. Good control in following seas, with little tendency to broach.

7. Moderate influence of heel on control. Excessive changes to the manoeuvring characteristics may occur when a boat is heeled, so that operation in waves or under the influence of other heeling forces becomes degraded.

Influence of Hull Design on Manoeuvring

There are a number of aspects of design which have significant influence on manoeuvring, but they are interdependent and changing one to improve a particular characteristic may have some detrimental effect on another characteristic. The following are considered to be the most important parameters.

1. Round bilge or chine configuration. There are many examples of both types of hull form with control problems, and examples where changes to the chine configuration has improved some aspect of poor behaviour.

2. Hull deadrise aft. In general, lower deadrise hulls, or those with excessive warp, are more prone to control problems.

3. Hull deadrise forward. High deadrise forward, resulting in deep forward sections, tends to reduce directional stability.

4. Distribution of lateral area. The longitudinal distribution, or location of the centre of lateral resistance (CLR), affects the directional stability, with increased area aft being beneficial.

5. Skegs and bilge keels influence the heel angle in a turn. They generate a side force directed into the turn and, being centred low down, this produces an outward heeling moment.

6. Longitudinal centre of gravity. This has two conflicting effects, a forward LCG promotes good directional stability by maintaining the centre of gravity forward of the CLR, in the same way as a dart with its weight forward and flights aft. A forward LCG will also trim the craft however, and this will reduce the directional stability by moving the CLR forward. The net effect will depend upon which of the two moves furthest.

7. Vertical centre of gravity. A high centre of gravity will increase the outward heel in a turn, and this may have a strong influence on the directional stability.

8. Trim control devices. By controlling trim with transom wedges, trim tabs, or variable drive angles, the directional stability will also be adjusted. Running with a low trim generally reduces the directional stability.

Model Test Objectives

Most aspects of the hull design will be fixed or guided by other design requirements, the owner's specification, or practical constraints, and the objectives of a model test programme probably will be to ensure that the proposed design has no adverse characteristics, or to set limits for those parameters which may have a practical range within the design envelope.

The propulsion arrangement, appendage configuration and rudder design will all influence the handling, and their effects are incorporated in a model test programme.

Depending upon the particular requirements of the project, the tests may be required to confirm or quantify some or all of the qualities listed above.

Modelling Requirements

Conventional ship model manoeuvring test techniques are described fully in Principles of Naval Architecture, published by SNAME. The ideal requirements for modelling include correct representation of the displacement and centre of gravity, yaw and roll moments of inertia, rudder deflection angle and rate, propeller slip ratio, and response of the propulsion motor to the increased resistance when turning. The type of test to be conducted, and the implications of the effects, should be considered before deciding whether each of these requirements needs to be met. For example, if the tests are only to include steady turns, there will be no need to model the moments of inertia or rudder rate.

For high speed craft, when the requirements include a study of the dynamic phases of the manoeuvres, it is important to match the displacement, LCG, VCG, yaw inertia and roll inertia. It is common for fast craft to trim down by the bow when helm is applied, so it is worth noting that, since for most monohulls the yaw inertia and pitch inertia are approximately the same, any dynamic effect of a manoeuvre on the trim will also be modelled correctly.

The maximum rudder deflection should be modelled if manoeuvres at full helm are to be conducted, but frequently it is the effect of small or moderate helm angles which are of most interest. Usually it is not difficult to model the correct angle however, and this gives to ability to make some assessment of the low speed manoeuvring qualities.

The rudder rate can be modelled by suitable choice of a constant speed servo and tiller length. In the two recent projects concerning boats at an early stage of their design, the helm rate was not known and so no attempt was made to fix the model rate. The rudder rates for small craft are relatively high in comparison with those for large ships and it is more likely that a model servo will approximately match the scale rate for a small fast craft.

To match the propeller slip ratio is rather problematic, since the viscous scale effects result in a relatively high model resistance in comparison with the full scale vessel. To overcome this difference an air screw may be fitted to the model to provide a small thrust equal to the difference between the model resistance and the ship resistance at model scale. A carefully engineered model of the full scale propeller is required, of a sufficient size that propeller scale effects are negligible. To satisfy this requirement requires large models and correspondingly large facilities in which to test them, with accurately modelled propellers typically costing several thousand pounds. The alternative approach frequently taken at the Wolfson Unit is to use a very simple model propeller which acts as a thruster rather than a model of the full size propeller. The propeller diameter is modelled correctly, and so the flow upstream and downstream of the propeller is representative. Speed of rotation is adjusted to achieve sufficient thrust and, being inefficient, the propeller will absorb relatively more power than at full scale. This enables the model size to be chosen on the basis of other practical considerations, and propeller costs are minimal.

The response of the propulsion motor to the increased resistance when turning will not be modelled in these simplified model tests, and so the reduction of speed in the turn will not be represented accurately. This may have other implications because heel angle in the turn, and turning circle diameter may be dependant on speed, but the effects are likely to be second order.

The high power to weight ratio of high speed craft presents a problem in scale modelling. The choice between electric propulsion and internal combustion engine must take account the short range or high battery weight of the former, and the complications and poor reliability of the latter. There is no doubt that electric motors offer substantial advantages in terms of controllability, ease of outfit, cleanliness, noise, and lack of pollution which may be a consideration if testing indoors. They have been used with sealed 6 volt lead acid batteries distributed to obtain the appropriate ballast requirements. The high power consumption may require water cooled speed controllers or motor jackets, but these are readily available modelling components.

Care must be taken in model design and outfitting, to ensure that all variable parameters can be measured, and that all controls are repeatable and calibrated. There may be hysteresis in a steering linkage for example, which will result in significant differences between rudder angles when the indicated angle is approached from port or starboard. The steering nozzles or vanes fitted to model water jet drives are calibrated with the jets developing the same thrust as at the test speed, but with the model tethered, because the measured angles are dependent on the flow speed.

The difficulty of calibrating standard radio control systems, and eliminating such problems as hysteresis, means that it is often preferable to use manual adjustment for as many variables as possible. Trim tabs are a typical example for, whilst it is essential to have control of them on the boat, it is not necessary to vary them during a single manoeuvring test. A simple manual adjustment is used to fix the tabs accurately to a known angle, with tests conducted at a range of angles if required. With tabs controlled via the radio, it is difficult to be certain of their angle during the test, particularly if their deflection is affected by the force on them at high speed.

To minimise cost, all measurements of speed, heading, heel, trim, and rate of turn are made from observations aided by video recording. To install measurement transducers and data logging systems into the models moves the complexity and cost into another category which generally is beyond the available budget and timescale.

Standard turbulence stimulation studs are fitted to ensure that the model boundary layer is representative of that at full scale.

One of the lifeboat models, complete with propellers in tunnels, rudders, trim tabs and bilge keels, is illustrated in Figure 1.

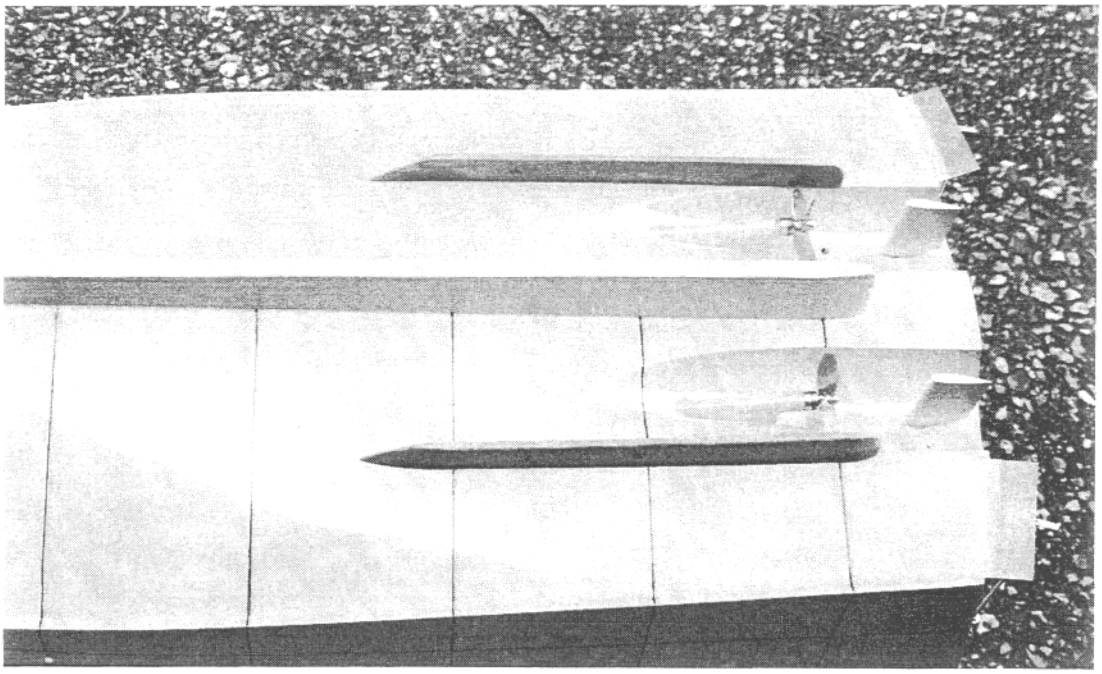

Figure 1

Techniques for Testing in Calm Water

Similar techniques were used in both propeller and jet driven models, but when conducting turns with jets, the vectored thrust remains relatively constant while the speed drops in the turn. As the speed reduces the turning circle diameter reduces, with further loss of speed. A steady rate of turn was achieved with jet propulsion, but a substantial settling period was required.

Speed and Trim Calibration

Speed is measured to calibrate the throttle settings by timing the model over a measured distance marked with transit posts. Trim can be estimated from the video image, but all of the designs tested at the Wolfson Unit have been tested in a towing tank prior to manoeuvring tests, and the trim characteristics have been well documented. If the relationship between speed, trim and the intersection of the running waterline with the bow profile is known, the latter provides a reliable indication of the trim and speed combination during the tests, often being the first indicator of a drop in battery power for example.

Dieudonne Spiral Test

The standard ship manoeuvre for determining the directional stability is the Dieudonne spiral. This involves timing the steady rate of turn at a range of rudder angles, and in particular at small rudder angles, with angles incrementing progressively from port to starboard through midships, and returning back to port. With an unstable vessel the turn to port will continue with helm amidships, or even with small starboard helm angles. The series of turns must be repeated for opposing rudder increments to eliminate any asymmetry in modelling or propulsion, or external effects such as the wind.

The importance of obtaining reliable data at small helm angles requires a large manoeuvring pond, and substantial endurance from the power source. If electric motors are used the short battery life may prevent constant speed turns of large diameter, although typically these small craft settle into a steady rate of turn very quickly, and the timing of a 180 degree turn following a 90 degree approach turn may be sufficient. To eliminate parallax errors, the rate of turn is best timed between the nearest and furthest points on the turning circle, by aligning two masts positioned in line athwartships.
Video freeze frame, and frame by frame time coding facilities give this method a high level of accuracy. Figure 2 shows a model which has just turned through the mast alignment position close to the camera.

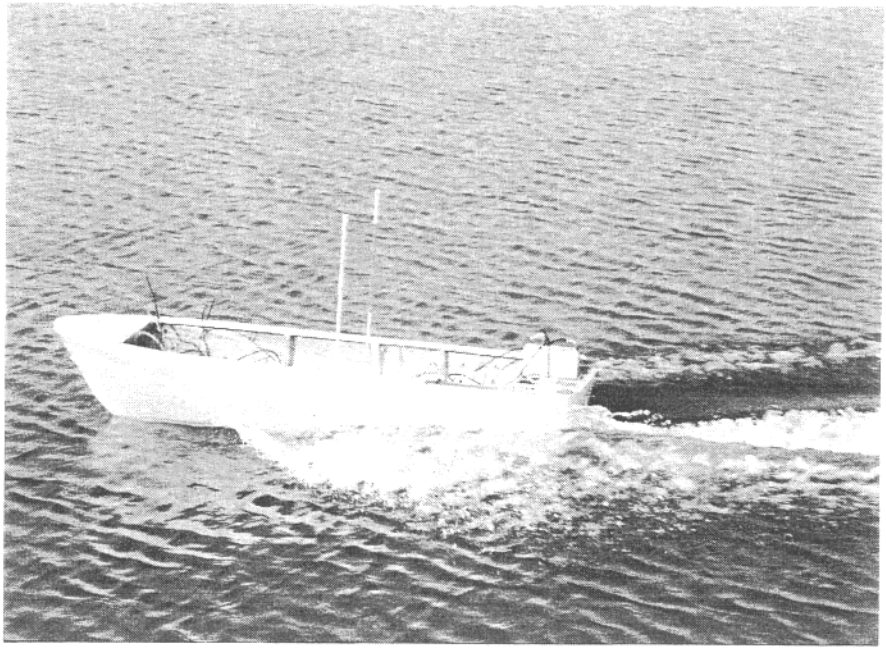

Figure 2

The view of the model from directly ahead or astern enables the heel angle in the turn to be measured, again with the aid of the masts, as in Figure 3.

Small Angle Zig-Zag Test

An alternative technique for determining whether the model has positive directional stability is to conduct a low angle zig-zag manoeuvre. The model is driven away from the controller who applies small helm angles alternately to port and starboard, applying starboard helm when a port turn has become established, and vice-versa. A stable model will respond to small helm changes by altering course accordingly, but an unstable one will require a substantial helm angle to pull out of a turn. The heading changes can be seen clearly if the model is heading away from or towards the controller and the result, albeit qualitative, is obtained quickly with minimal battery consumption. This technique is very useful in tests where a large number of model configurations need to be tested, and to conduct full Dieudonne spiral tests on each one would be too time consuming.

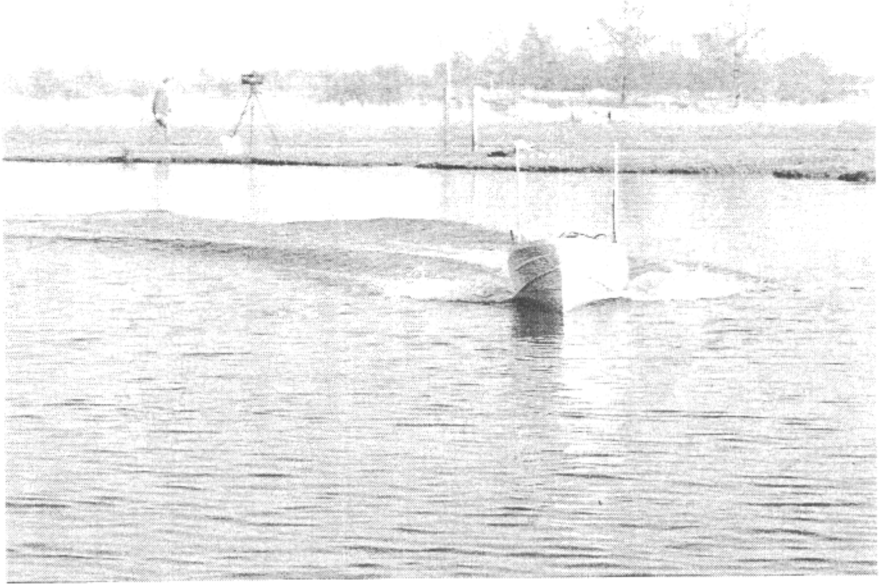

Figure 3

Large Angle Zig-Zag Test

The zig-zag test is a standard ship manoeuvre which provides information on the hull characteristics, rudder performance and control system. In a 20-20 zig-zag manoeuvre the helm is put over to 20 degrees to port, and when the heading alters to 20 degrees off the original the helm is put over 20 degrees to starboard. This cycle is repeated a number of times and measurements made of the ship response in terms of the times of events, the maximum heading changes and the maximum distances off the original track. Such trials are difficult to conduct with fast models under manual control, but less precise large angle zig-zag tests provide a useful opportunity to observe the control qualities and heeling response to the helm. Tests with 20 degrees or full helm indicate the heeling response to the helm, the heel angle in the established turn, and quickly highlight any asymmetry in the model or control system. See Figure 4.

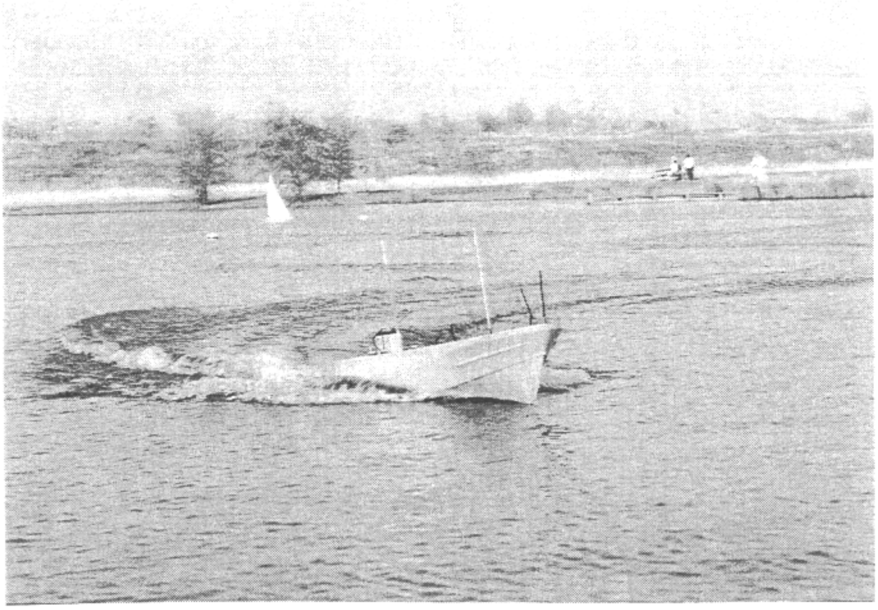

Figure 4

Dynamic Heeling Test

With some ballast moved to one side of the model to achieve a static heel angle of about 5 degrees, the model is driven away from the operator, and helm applied as required to maintain a straight course. An increase in the heel angle will indicate a reduction in stability with speed. When heeled, most boats generate a yawing moment which turns the boat in the opposite direction to the heel, and this test also provides a measure of this tendency by the helm required to correct it.

Techniques for Testing in Waves

The self propelled model can be operated in a manoeuvring basin with wave making facilities, and this provides an opportunity to observe its behaviour running at any heading in a seastate. One of the most important requirements for fast craft is the ability to operate in stern and quartering seas with sufficient control to avoid or pull out of a broach. At other headings, however, the waves are unlikely to cause problems with the control which are not exhibited in calm water. A large manoeuvring basin tends to be an expensive facility to hire and, if used for runs in stern and quartering seas only, may be inefficient.

The towing tank offers an attractive alternative if it has sufficient width to enable zig-zag manoeuvres in stern seas. The self propelled model can be controlled and filmed by personnel on the carriage, which can follow the model along the tank. This procedure gives the controller considerably more feel for the responses of the model than he has when controlling at a distance from the side of the manoeuvring basin, because he is close to, and above the model, looking in its direction of travel. He is better able to judge the position and speed of the model relative to the waves, and take appropriate actions to initiate and pull out of potential broaching situations. Similarly, the video record is taken from a more useful viewing position than is possible in the manoeuvring basin, and enables better observation of model heel and yaw responses.

In either case the procedure adopted has been to run the model in steep regular waves which have a celerity (wave speed) similar to the operational speed of interest. The model can then be positioned as required on a wave, and run obliquely or in a zig-zag manoeuvre. A particularly useful test is to run the model obliquely on the face of a wave, and then attempt to turn down the wave to take it directly astern. This simulates the broaching scenario and the level of control which is available.

Representative irregular sea spectra might be expected to provide more realistic conditions, but because there are a low number of wave encounters in a given run, many runs are required to provide encounters with sufficiently steep waves to challenge the capabilities of the model.

Sample Results

Figure 5 presents Dieudonne spiral data obtained with a propeller driven model tested with three different VCG values. Tests were conducted for a range of rudder angles, and the measured rates of turn were non-dimensionalised with respect to speed. With the lowest VCG the linear nature of the data indicate high directional stability. With the increasing VCG height the data become less linear as directional stability decreases, and with the high VCG the discontinuous curve reveals that the model was directionally unstable.

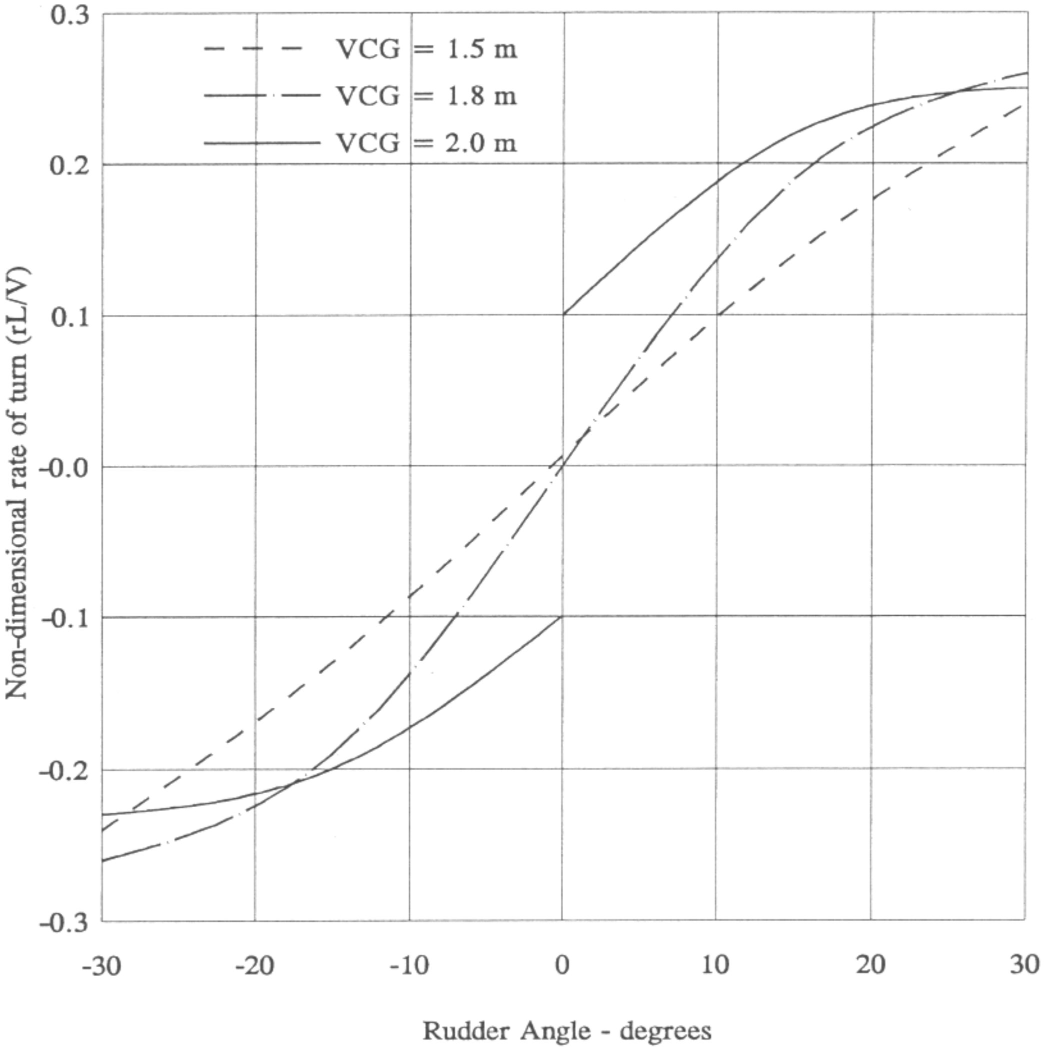

Figure 5: The Effect of VCG on Rate of Turn

Figure 6 gives a clue as to the reason for this high sensitivity to VCG, showing the effect of VCG on the heel angle in a turn for the same model. This model heeled outwards during turns unless the VCG was very low. As VCG was increased, the heel outwards increased, and the model's rate of turn at low and moderate rudder angles increased as a result of the heel angle.

Table 1 presents further results for this model, to include the effects of LCG on the directional stability. In the case of the mid VCG height, the model was stable until the LCG was moved well forward of the design location. It suggests that the VCG dominated the behaviour, but when the stability was marginal the effects of LCG also became important.

VCG metres	LCG - metres forward of design		
	-0.2	Design	0.2
1.5	Stable	Stable	Stable
1.8	Stable	Stable	Poor
2.0	Unstable	Unstable	Unstable

Table 1. The Effect of Centre of Gravity on Directional Stability

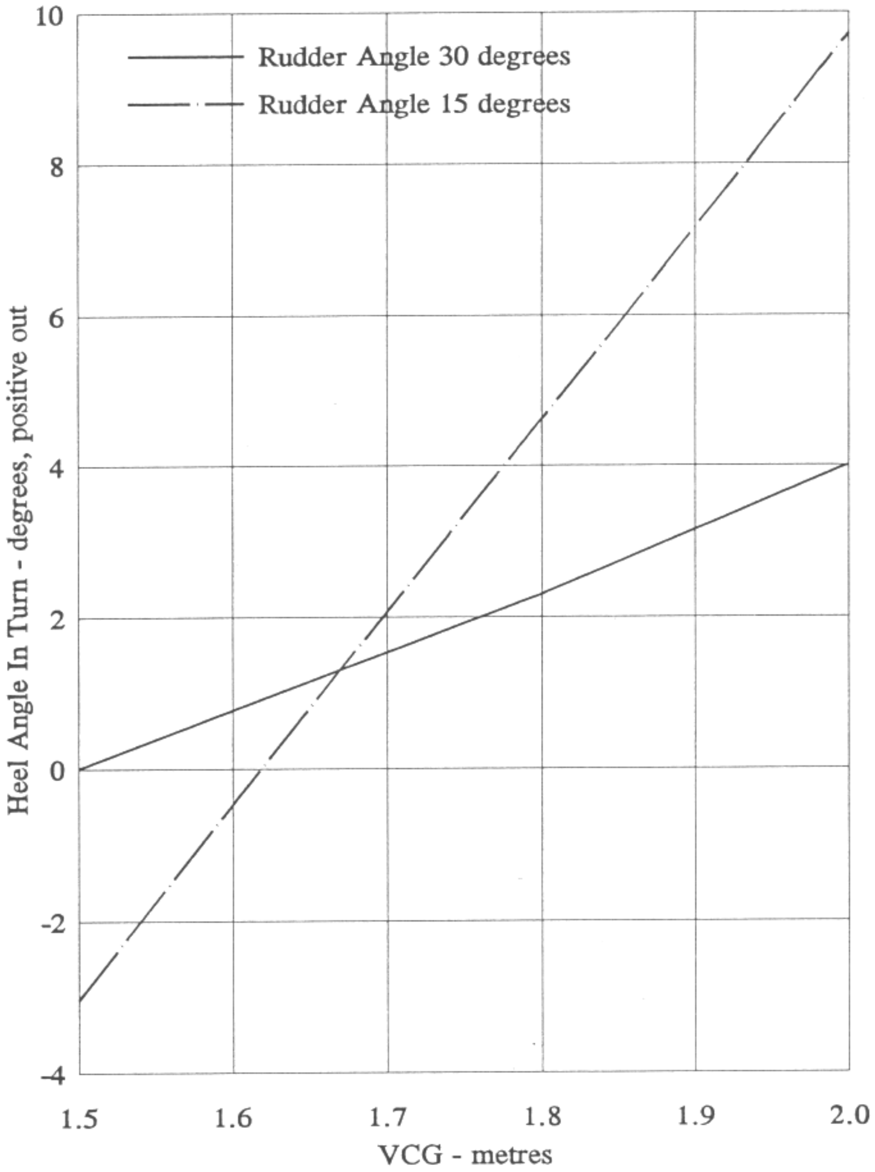

Figure 6: The Effect of VCG on Heel Angle in a Turn

A model of a different design always heeled into the turn, and proved relatively insensitive to VCG. When heeling into the turn, the induced yaw moment tends to reduce the rate of turn, and a larger helm angle is required to maintain a continuous rate of turn. For this design the handling was found to be more dependent on the trim, and at excessive trim tab angles the model was notably less responsive. Figure 7 shows data obtained from the dynamic heeling test for this model with a range of LCG values. When heeled to starboard the model tended to turn to port, and the starboard helm required to maintain a straight course increased with increasing trim by the bow.

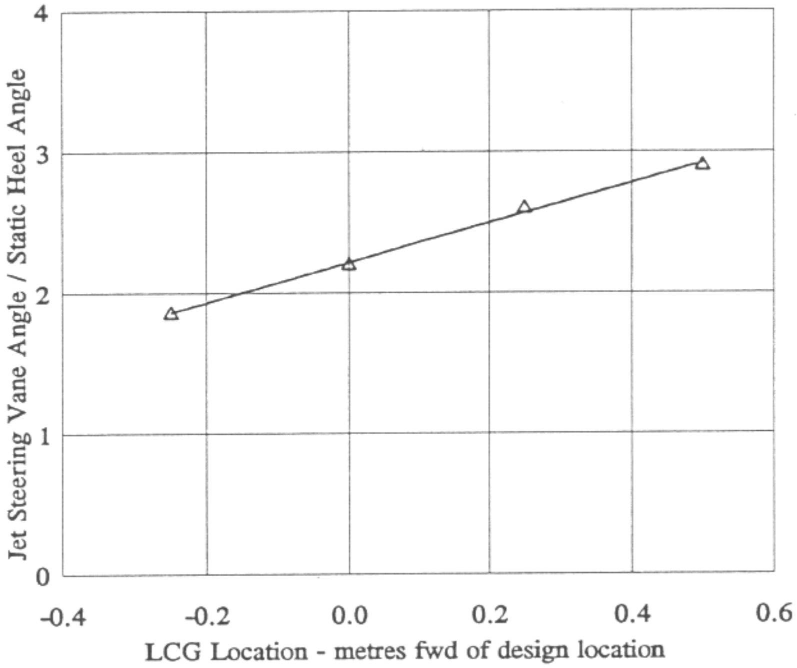

Figure 7: Helm Required to Manintain a Straight Course When Heeled, and its Variation with LCG Location

This is a normal result, and helps us to understand the problem of broaching. When a wave approaches from the port quarter, the boat accelerates down the face of the wave, and heels to starboard. The heel induces a turn to port, along the face of the wave, and probably against the wishes of the helmsman who will attempt to turn to starboard to take the wave astern. If the trim tabs are down, the normal bow up trim will reduce as speed increases, and the yaw moment to port induced by heeling may be so great that a large starboard helm angle is required to counteract it. This may leave little additional helm angle with which to turn the boat to starboard. This scenario was exhibited on several occasions when testing particular model configurations in quartering seas in the towing tank or manoeuvring basin, and collisions with the tank side were the result.

Acknowledgements

The author is grateful to the RNLI and Halmatic Ltd. for their permission to use data and photographs to illustrate this paper.