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Analysis of Hull Shape Effects on Hydrodynamic Drag in Offshore Handicap Racing Rules

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ABSTRACT

US Sailing and the Institute for Marine Dynamics (IMD) in St. John's, Newfoundland, are collaborating in a joint research program to investigate the effects of hull shape variations on hydrodynamic drag. The results of this program are being used to support the development of rules that handicap racing yachts.

A fleet of 9 models has been designed with systematic variations in the most fundamental parameters: displacement and beam for fixed length. Six of those models have been tested both appended and bare-hull, in calm water and head seas. Analysis of residuary resistance, both upright and heeled, has been used to improve the Velocity Prediction Programs (VPPs) employed by both the International Measurement System (IMS) and AMERICAP rules.

NOTATION

LVR	Length Volume Ratio = Hull sailing length / (Hull volume) ^(1/3)
BTR	Beam Draft Ratio = IMS Rule integrated beam draft ratio
LBR	Length Beam Ratio = Hull sailing length / IMS integrated beam
Fn	Froude number, non-dimensional speed where $Fn = \text{velocity} / (\text{gravity} * \text{length})^{.5}$
Re	Reynold's number = velocity * length / kinematic viscosity
Q	Dynamic Pressure = $.5 * \text{density} * \text{velocity}^2$
Drag	(Resistance) Hydrodynamic force parallel to direction of motion through water
Drag Area	Drag / Q

INTRODUCTION

In 1996 the Institute for Marine Dynamics and US Sailing began a collaborative tank test program. This was initiated by Bruce Parsons of IMD as a follow-up to their successful work for the One-Australia America's Cup program for 1995. The dynamometer at IMD is designed to tow models that are approximately 1/3 of full-scale ACC yachts. That dynamometer is also quite rigid, enabling a high degree of accuracy.

The intended beneficiaries of this test program included the science-based offshore race handicapping IMS and AMERICAP Rules. Since the details of the AMERICAP VPP are not public, the discussion in this paper will reference the IMS Rule only.

By 1996 the IMS rule had gone through a period of yearly changes to the resistance model, with resultant dramatic shifts in boat ratings. The primary source of those changes was the formulation for residuary resistance (primarily wave drag.) Therefore the test program had, as its highest priority, the investigation of residuary resistance of hulls, both upright and heeled. The scope of the program was expanded to include hull shape effects on lift-induced drag and added resistance in waves.

In the IMS Rule, residuary resistance is modeled with a regression fit to a database of tank test results. The fit is a linear combination of terms using the principal hull shape parameters considered to influence residuary resistance. A description of this regression is in Claughton, 1999. The tank test database consists of several parametric series of models tested at Delft University, Gerritsma 1981 and 1993, Keuning 1996, and at the University of Southampton. Changes to the IMS predictions of residuary resistance can occur either through changes in the regression formula or changes to the tank test database, through addition of new model tests or subtraction of existing ones.

DESIGN OF IMD TANK TEST PROGRAM

ITC Test Fleet

The International Technical Committee (ITC) of the Offshore Racing Council (ORC) is responsible for the technical development of the IMS rule. A critical method for checking the overall sensibility of proposed rule changes is to test those changes on a large fleet of known boats. Boats represented in the fleet include contemporary racers as well as boats of highly diverse characteristics that run the gamut of design.

Figure 1 shows a scatter cloud of the ITC test fleet, circa 1996, in which length beam ratio (LBR) is plotted against canoe length volume ratio (Canoe LVR). The length, beam and volume used are IMS parameters and described by Claughton, 1999. For a given length, the displacement and beam are arguably the 2 hull parameters that have the greatest influence on residuary resistance. LBR and LVR are convenient non-dimensional ratios that describe beam and displacement at fixed length.

This scatter cloud, then, is a plot of the range of variation, within the ITC test fleet, of these fundamental parameters. Clearly, there is coupling between LVR and LBR. Lighter designs tend to have reduced beam. A series of models was chosen to bracket both the LVR and LBR ranges. A three by three matrix of models, with LBR variations at each of three LVR values was the result. These are plotted in Figure 1 as open squares connected with dashed lines. Models are designated 1 through 9, with Model 5 being the central, or parent, design.

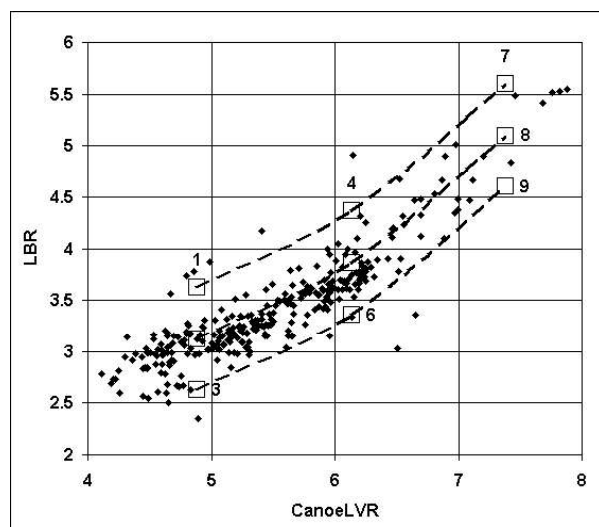


Figure 1 – ITC Test Fleet, LBR vs. Canoe LVR

Figure 2 shows BTR plotted vs. LVR for the same fleet. BTR is an IMS hull parameter that represents an integrated beam draft ratio. In the test fleet, there are two boats, with an LVR near 6.6 that show extremely high BTR values. This same pair is seen in Figure 1 as having low LBR values. This pair illustrates that there are boats

with atypical, perhaps extreme, parameter values racing under handicap rules. The IMD/US Sailing program does not have the scope to cover every boat that the IMS rule tries to handicap. However, it does have sufficient breadth to capture hydrodynamic trends across the bulk of the IMS fleet and, with a series of three point variations, it has the ability to discern non-linear behavior.

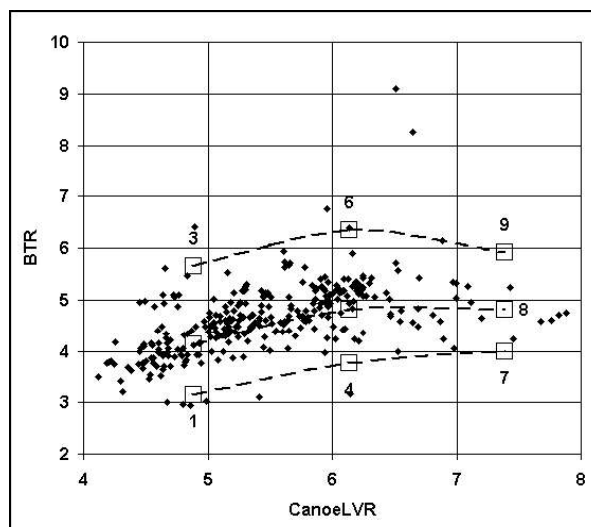


Figure 2 – ITC Test Fleet, BTR vs. Canoe LVR

A summary of these length, beam and displacement ratios for all the models is listed in Table 1:

Model:	1	4	7
LVR	4.886	6.131	7.412
LBR	3.625	4.353	5.494
BTR	2.755	3.859	4.010
Model:	2	5	8
LVR	4.886	6.137	7.423
LBR	3.125	3.862	5.012
BTR	3.707	4.810	4.765
Model:	3	6	9
LVR	4.886	6.149	7.436
LBR	2.625	3.415	4.530
BTR	5.254	6.063	5.786

Table 1 – Model Fleet Hull Parameters

Test Models

The characteristics of Model 5, the parent test model are those of the middle square in Figures 1 and 2. It has an LVR equal to 6.14, LBR equal to 3.86 and BTR equal to 4.81. The hull lines of the model were not optimized to any particular rating rule, but were intended to be a smooth, fast shape. A number of design offices, active participants in the IMS Rule, contributed to the development of the lines of this parent, along with the design of the entire program. The body plan for the parent design, Model 5 is shown in Figure 3. Body plans for Models 4 through 9 are provided in the appendix.

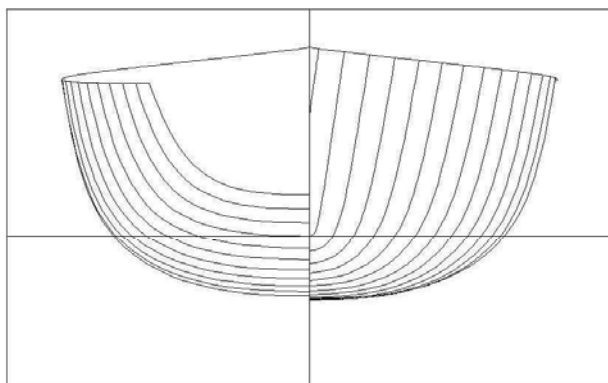


Figure 3 – Model 5, Parent Design for Series

Test program

The models were tested in calm water with and without appendages, upright and heeled. A number of tests were run at low speeds to enable Prohaska analysis, see Teeters 1993. The speed range then extends up to a Froude number of .6, the highest speed that IMS currently uses in its handicaps. (It should be pointed out that during its November '02 annual meeting, the ORC decided to include water-ballasted boats into the IMS rule. This greatly opens up the potential for boats to exceed F_n .6 sailing offwind and the IMD program is being modified accordingly.)

The models were tested at heel angles of 0, 15, and 25 degrees. At each heel angle, there are leeway sweeps at each of 3 speeds, corresponding to Froude numbers of .25, .325, and .40. The leeway sweeps are from 0 to 6 degrees in 1 degree increments. Rudder angles were always set equal to the leeway angle, a practice that is systematic and defines a relationship between leeway and rudder angle similar to that measured on sailboats. On the other hand, as shown by Teeters, Pallard, Muselet, 2002, there are situations where optimal hydrodynamics can be achieved using large rudder angles, far in excess of the leeway angles.

Although not presented in this paper, the analysis of induced drag in the IMD series will have implications for the prediction of IMS effective draft. Additionally, head seas tests, upright and heeled, were conducted to generate a database for future work on added resistance in waves.

Model 5, funded by the Cruising Club of America, was tested in 1996. In addition, Models 4, 6, 7, 8, and 9 have been tested with financial support from US Sailing's McCurdy Fund and the US Sailing Foundation.

RESIDUARY RESISTANCE UPRIGHT

For a handicapping VPP, such as that used in the IMS Rule, perhaps the most critical measure of its utility is the accuracy in predicting trends, differences, rather than absolutes. This trending is commonly expressed as

differences in rating, typically seconds per mile, due to measured differences in a boat or between boats. It would be nice if the magnitude of boat speed predictions were highly accurate, but to provide fair racing it is generally sufficient to achieve accuracy in the time differences owed between boats. With that in mind, much of the analysis presented in this paper is expressed as trends, changes in hydrodynamics due to changes in model design. Specifically, trends from the towing tank are compared with those from the IMS Rule.

Moderate Displacement Series vs. IMS99

Figures 4, 5, and 6 show curves of upright residuary resistance derived from both the IMD tank tests and from the VPP predictions of the 1999 IMS Rule. This particular version of the VPP was chosen since it was the last one that did not include the IMD model data. In other words, this comparison shows how well the IMS Rule could predict the drag of the first three IMD models without specific knowledge of the hydrodynamics of those designs.

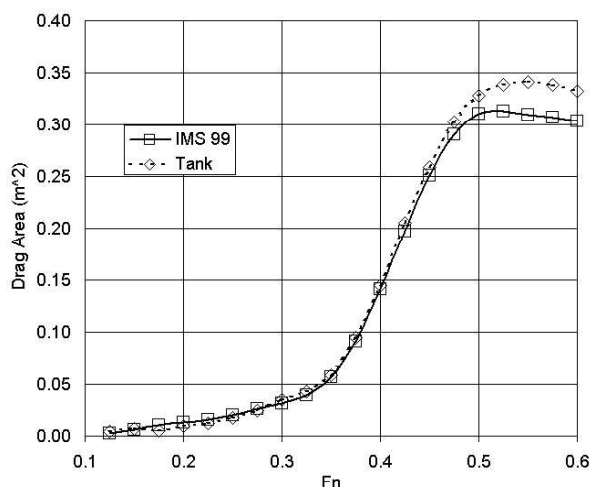


Figure 4 – Model 4 Upright Residuary Resistance

In the IMS protocol of accounting for hydrodynamic drag, the residuary resistance is the drag remaining after estimates of viscous drag are subtracted from total drag, as measured in tank tests of bare hulls (no appendages.) To make valid comparisons of IMS predicted drag with new tank data, it is necessary to repeat the same protocol in analyzing that tank data. Very briefly, this protocol uses a Reynold's number length of 70% of the IMS canoe effective length. There is no Prohaska form factor effect. The wetted area at each heel angle is used for the prediction of viscous drag. Since the primary component of residuary resistance is the drag associated with the generation of free surface waves, residuary resistance is often called wave drag.

As seen in Figure 4, IMS99 did a reasonable job of predicting the drag of IMD Model 4, except at high boat speeds. This error at high speeds is certainly a concern,

but the concern is mitigated by the fact that boats rarely reach these speeds in the sailing conditions used to construct IMS handicaps. Nevertheless, in light of the coming inclusion of water-ballasted boats and, potentially, of canted-keel boats, we will be seeing more boats that can reach F_n greater than .5. The error in drag prediction at high F_n will have increased significance in IMS racing.

The Model 5 comparison, shown in Figure 5, is similar. The under-prediction above a F_n of .275 has become significant and the error above .5 is still quite large.

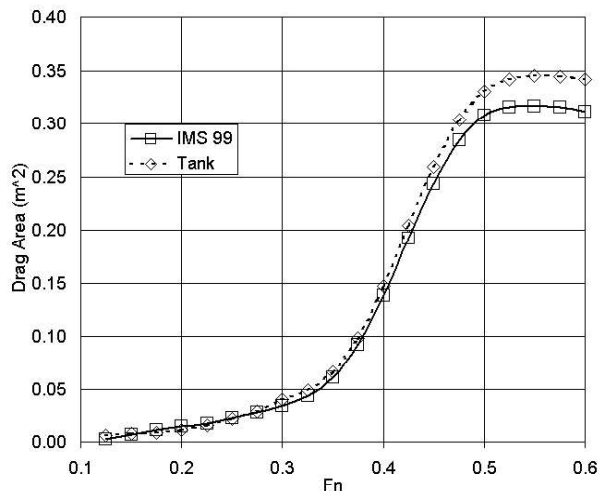


Figure 5 – Model 5 Upright Residuary Resistance

In Model 6, Figure 6, there is an even larger discrepancy between tank test and VPP prediction. As the discrepancies have been getting progressively larger with beam (Models 4, 5, and 6 is a beam series) it makes sense to tabulate the errors and examine the variation across beam.

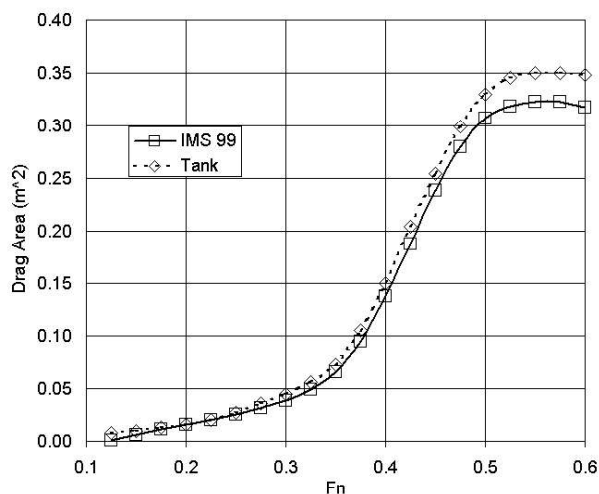


Figure 6 – Model 6 Upright Residuary Resistance

Figure 7 shows the residuary drag deltas as the beam increases. The drag of Model 4 (narrow) is subtracted

from that of Model 5 and the drag of Model 5 is subtracted from that of Model 6 (wide). A positive drag difference therefore indicates an increase in drag with an increase in beam. That this drag delta is positive is nothing new. The IMS rule, since its inception as MHS in 1978, has predicted an increase in residuary resistance with beam (Kerwin, 1978.) What is interesting is that the tank results show a decrease at relatively high F_n from .4 to .5.

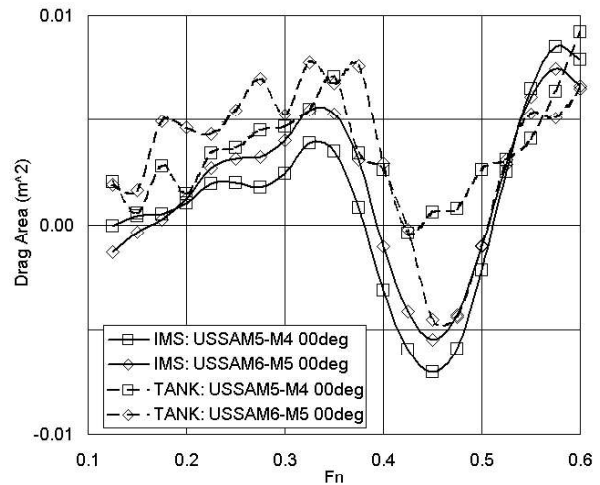


Figure 7 – Model 4, 5, 6 Drag Differences, IMS99

The tank data confirm the trends shown in the IMS 99 Rule, but also indicate that there is a greater increase in drag with beam than the rule predicted. This, disregarding any other aspects of the rule, would suggest that narrow beam would be favored in IMS99, that the rule does not give sufficient drag “credit” for wide beam.

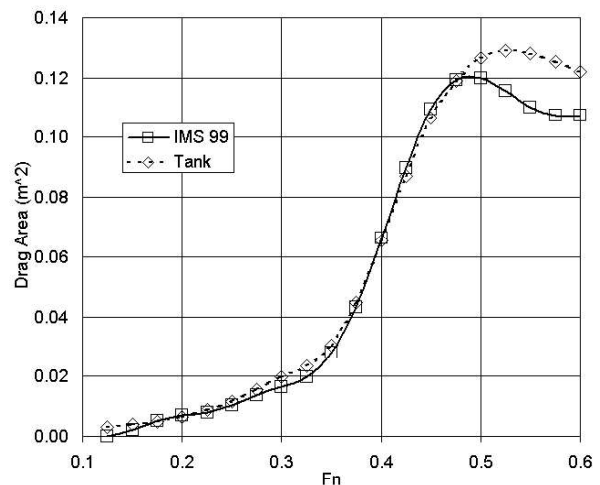


Figure 8 – Model 7 Upright Residuary Resistance

Light Displacement Series vs. IMS99

Figures 8, 9 and 10 show comparisons of predictions from IMS99 with tank test results for the light displacement series, Models 7, 8, and 9. There are trends similar to those for the heavy model series.

The prediction for the narrow boat, Model 7, Figure 8, is a bit low between F_n .25 and .35, quite good between .35 and .45 and quite bad at the top speeds. The predictions for Model 8, Figure 9, are even lower than the tank results between F_n .25 and .35. For Model 9 the wide and light boat, there is a still greater under-prediction, seen in Figure 10 that extends up to high F_n sailing.

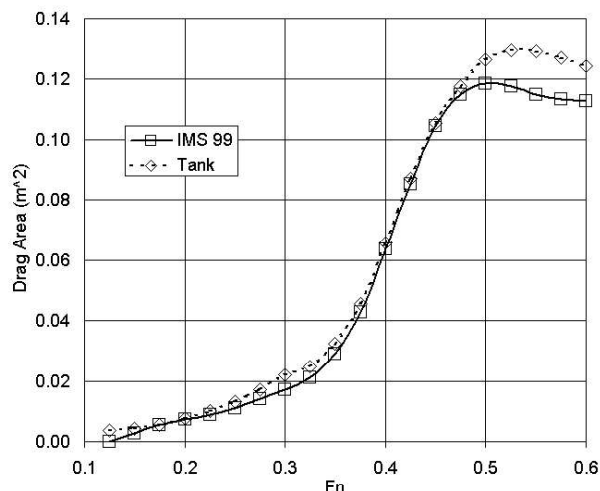


Figure 9 – Model 8 Upright Residuary Resistance

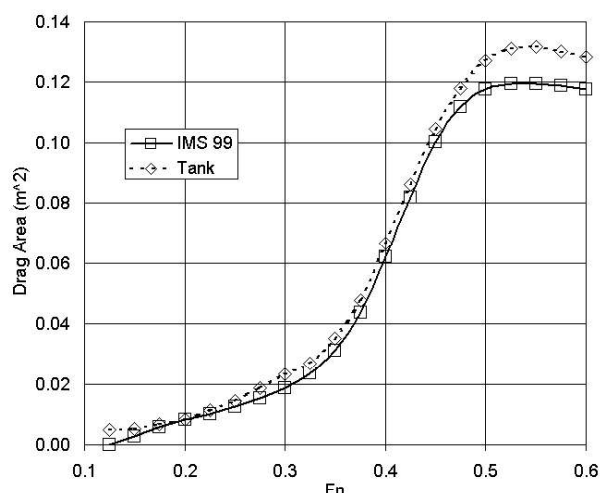


Figure 10 – Model 9 Upright Residuary Resistance

Figure 11 shows the same type of analysis as Figure 7, but this time the drag differences are for the lighter models. Because the residuary drag of the light model series is approximately $\frac{1}{2}$ that of the heavier models, the scale of Figure 11 is $\frac{1}{2}$ that used in Figure 7. This figure exhibits much the same trending as Figure 7. IMS99 shows less increase in drag with beam than the tank series. At moderately high F_n , centered at a value of .45, there is a very strong predicted drop in drag with beam, a trend that is much smaller in the tank results.

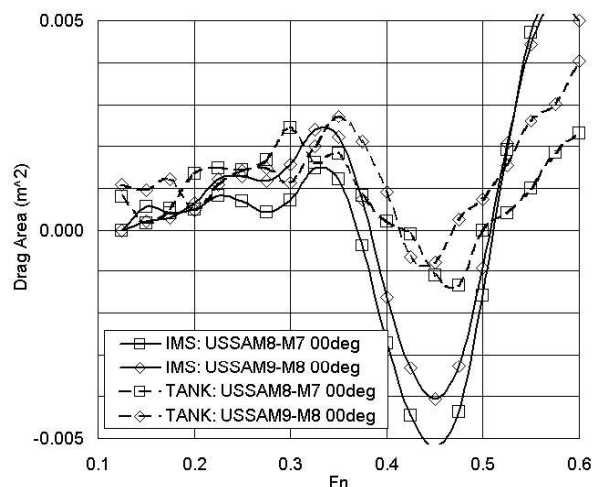


Figure 11 – Model 7, 8, 9 Drag Differences, IMS99

Summary of Drag Deltas vs. IMS99

Figure 12 shows % errors between the tank test data and VPP predictions. A positive value denotes that IMS99 over-predicts residuary resistance. It is difficult to express residuary resistance changes as % of total residuary resistance at low speeds since the resistance becomes quite small. Therefore, no results below F_n .25 are shown.

On average, IMS99 under-predicts the drag of the models, as seen in the charts earlier presented. Figure 12 illustrates how much greater the under-prediction is for the light Models, 7-9, than the heavy models in the F_n range of .25 to .375. The opposite is true above .375.

The obvious conclusion is that light boats, or at least the IMD light boats, are less favored by IMS99 than heavier boats when sailing at F_n below .375. Since most of IMS handicapping is based on speed predictions below .375, it is safe to say that light boats are disfavored by the IMS 99 residuary resistance formula.

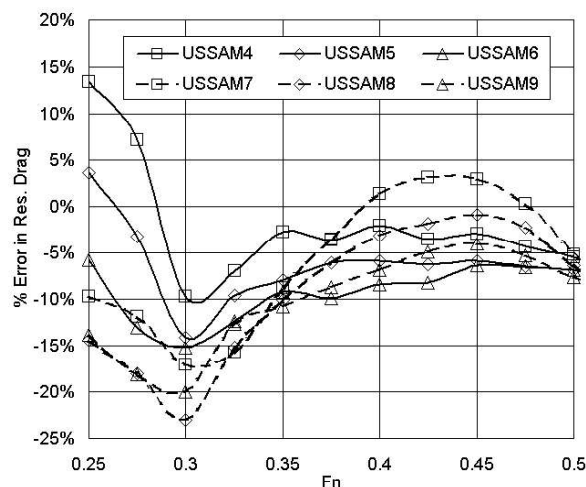


Figure 12 – Absolute Errors in Upright Drag, IMS99

Changes to the IMS Residuary Resistance Model

In November of 1999, the International Technical Committee modified the VPP formula for residuary resistance. The numerical regression method was unchanged, but the database of models used to generate the regression coefficients was. In addition, IMD Models 4, 5, and 6 were added and several existing models with extreme hull form parameters were eliminated. The result of changing the model database was a significant shift in the predictions of residuary drag. Naturally, the fit to the IMD series was improved.

Moderate Displacement Series vs. IMS01

Figure 13 shows IMD Model 4 data along with the new predictions from the IMS01 Rule. Clearly the fit is improved from that shown earlier in Figure 4. Figures 14 and 15 show an even greater improvement.

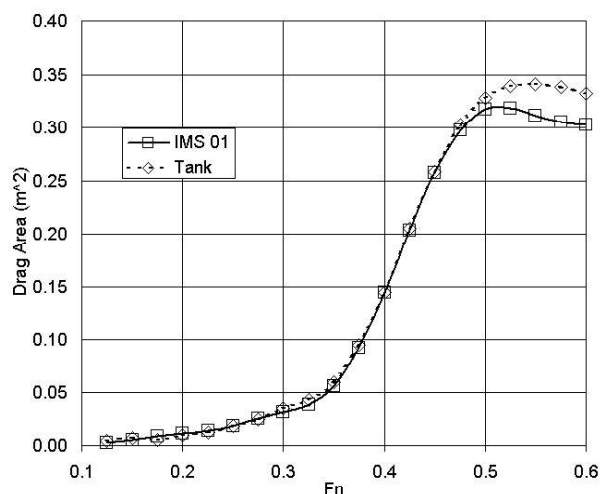


Figure 13 – Model 4 Upright Residuary Resistance

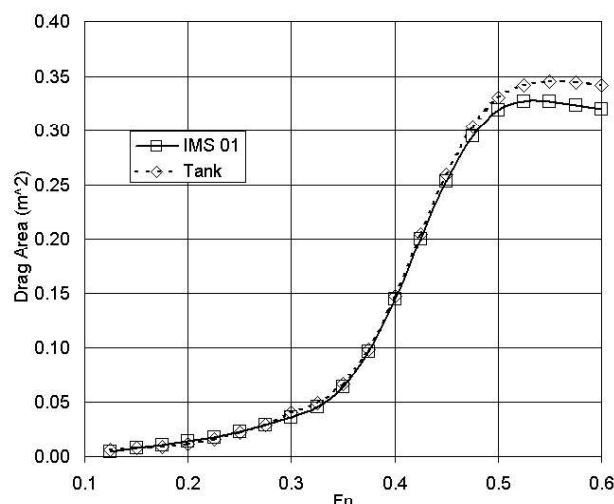


Figure 14 – Model 5 Upright Residuary Resistance

Figure 16 shows the close correlation between towing tank and IMS01 in predicting the changes in drag between models. The curves of IMS and tank data more

nearly lie on top of each other than in Figure 7. This was seen as a very positive step in improving the accuracy of the IMS Rule.

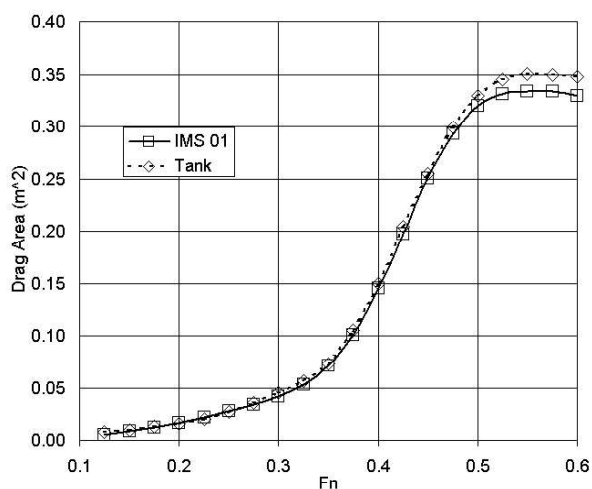


Figure 15 – Model 6 Upright Residuary Resistance

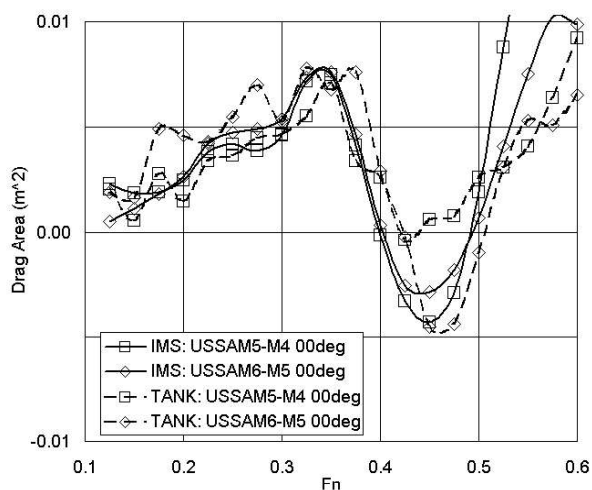


Figure 16 – Model 4, 5, 6 Drag Differences, IMS01

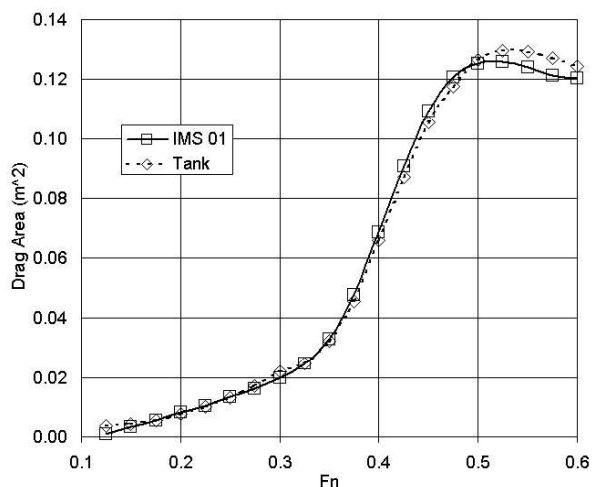


Figure 17 – Model 8 Upright Residuary Resistance

Light Displacement Series vs. IMS01

The light displacement series of models was tested only recently and has not yet been incorporated into the IMS Rule. As is to be expected, the predictions for these models will not be as accurate as for Models 4, 5, and 6.

As an example, Figure 17 shows the results for Model 8. This is certainly better than the previous fit shown for Model 8 with IMS99, Figure 9.

Figure 18 shows the absolute drag errors with IMS01 and should be compared with Figure 12 and the IMS99 errors. The improvement in the VPP is obvious. This improvement extends to the predictions of the light model series whose test results, again, have not yet been incorporated into the rule.

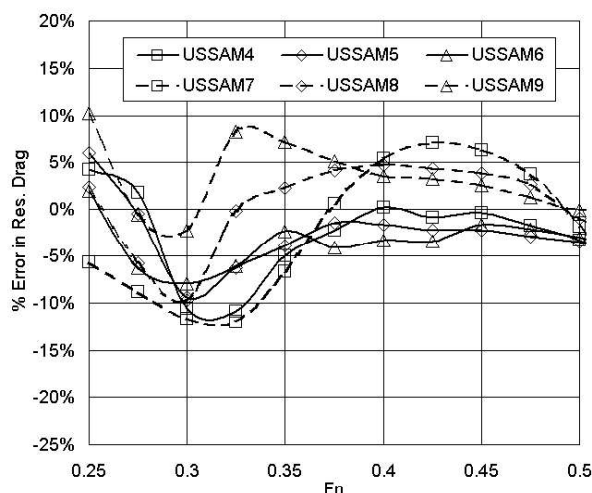


Figure 18 – Absolute Errors in Upright Drag, IMS01

Assessing Rule Changes

The above analysis supports the conclusion that the IMS Rule predictions of residuary resistance were improved from 1999 to 2000. Given the stated mission of the IMS Rule to fairly handicap a diverse fleet, this is probably true.

However, the IMS Rule has also been the home of a highly visible group of racing boats that optimize against the rule, seeking a rated vs. actual performance edge that gives an advantage over boats not optimized. For this group, any rule change has the potential to cause disruption.

The following are accepted as “facts of life” in the development of handicapping rules:

1. no change to a handicapping rule gives precisely accurate results, and
2. every change, no matter how defensible, will cause unhappiness somewhere.

All in all, the change to residuary resistance for the IMS Rule gave better handicapping to the large group of boats not optimized to the rule.

RESIDUARY RESISTANCE HEELED

The IMS Rule does not use an explicit calculation of heeled residuary resistance, see Claughton 1999, but generates a curve of multipliers, varying with Froude number, that are applied to the sum of upright hull and appendage residuary resistances. The principal determinants of the multiplier curve are the ratio of heeled to upright sailing length, the length displacement ratio of the boat, the heel angle, and the speed or Froude number. There is no term related to beam in this formula, although it must be stated that, as seen above, wide boats have more upright residuary resistance and any multiplier will accentuate that.

In any case, exploring the effects of beam on heeled residuary resistance at constant length and displacement has always been the principal motivation behind the entire IMD test program.

Figures 19 through 24 show the ratios of heeled to upright residuary resistance. The solid curves show the IMS predicted ratios, the dashed curves the actual tank test ratios. For Models 4, 5, and 6, the IMS curves are all very similar because they have similar values of the parameters that are used in the heeled drag ratio algorithm: length and displacement. The same comment is true for Models 7, 8, and 9. However, the values of these ratios for the lighter models are substantially greater than for the heavier models, illustrating the dependency of the heeled drag formula on displacement length ratio.

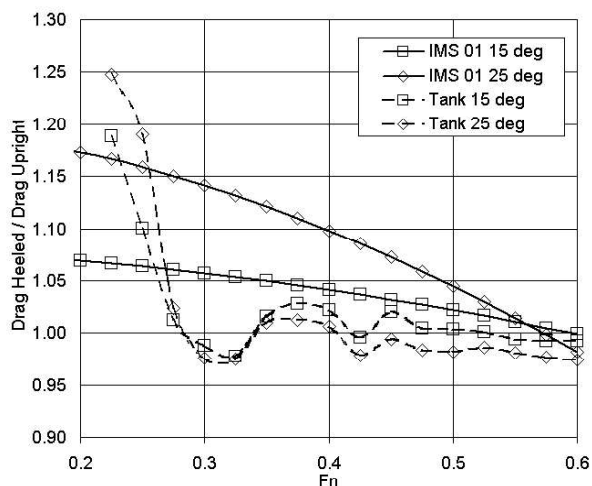


Figure 19 – Model 4 Heeled Drag Ratios

The IMS predicted curves are quite smooth, always convex downwards, showing a high ratio at low Froude numbers that diminishes to a value close to unity at the highest speeds. Important to observe is that the prediction across heel angle is non-linear. At all but the highest speeds, the increase at 25 degrees is over twice that at 15 degrees.

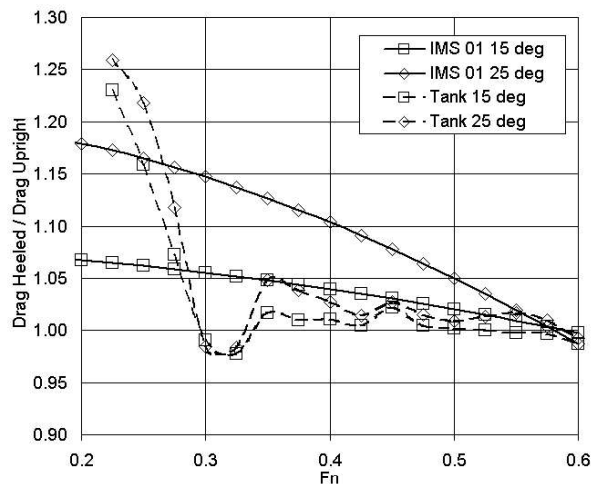


Figure 20 – Model 5 Heeled Drag Ratios

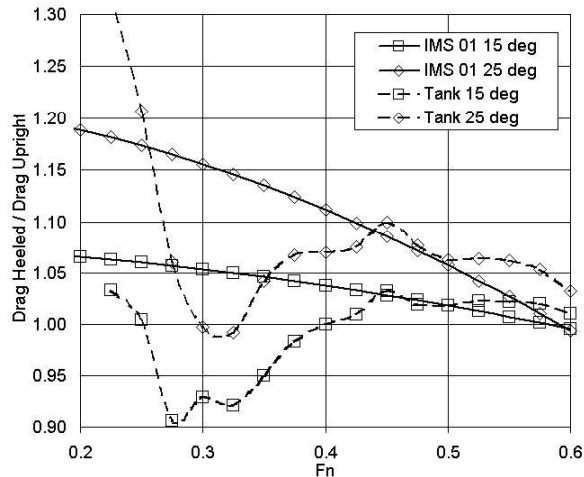


Figure 21 – Model 6 Heeled Drag Ratios

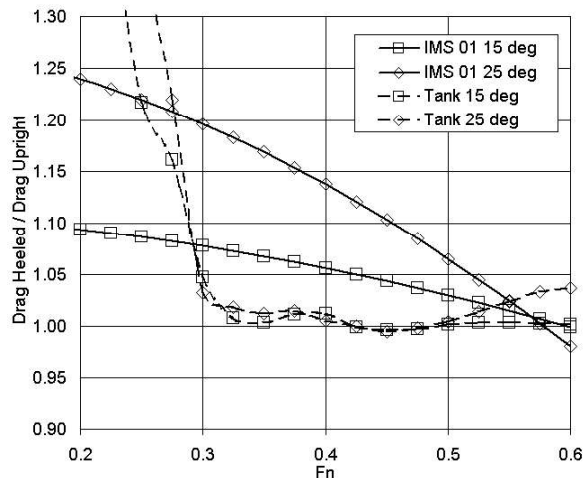


Figure 22 – Model 7 Heeled Drag Ratios

In contrast, the tank-generated data shows very different trends between models and very different trends with Froude number. Typically, the ratio of heeled to upright drag at low speeds is high with a fair amount of uncertainty. Again, the uncertainty is the result of taking

the ratio of 2 small numbers. What is clear in all cases is that the ratio drops very quickly, usually by Froude number .3, and levels off. The current IMS scheme can be said to have some correlation with the test data only at very low and very high boat speeds, but not at the intermediate speeds where most of sailing and, therefore, handicapping occurs.

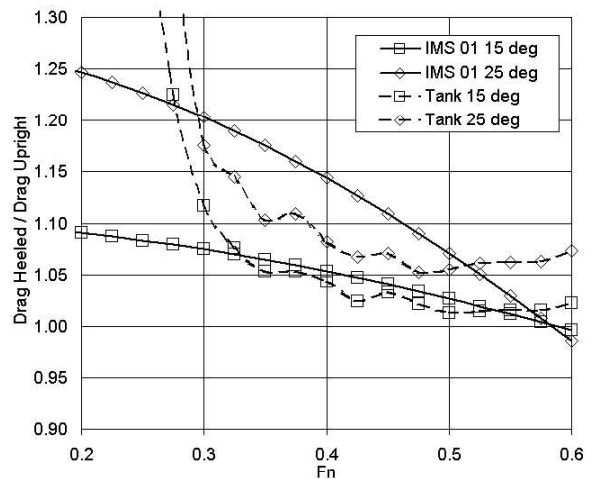


Figure 23 – Model 8 Heeled Drag Ratios

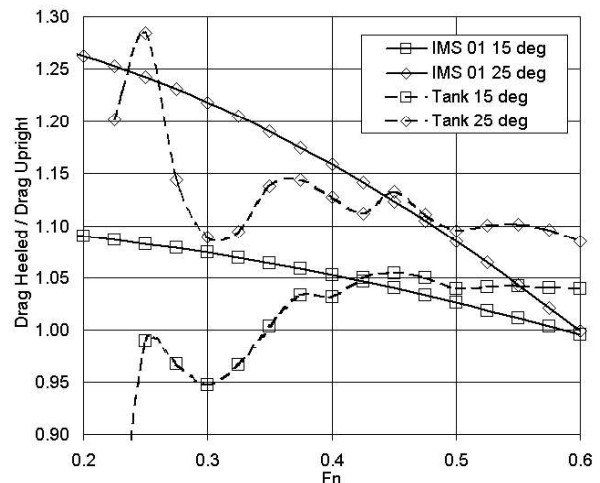


Figure 24 – Model 9 Heeled Drag Ratios

Part of the quick drop at Froude number .3 is the result of appendage residuary resistance. Figure 25 shows the implied residuary resistance of the keel and rudder at all three heel angles across the speed range. This implied appendage drag is found by taking the differences between the residuary resistances found from tank tests with and without appendages. Clearly, there is a reduction in this resistance at Froude number .3. This trend is exhibited by all the models and is generally attributed to the constructive interference of waves generated by the keel with those generated by the hull.

Of great significance is that the tank test derived curves for 15 and 25 degrees heel are close to each other for the narrow models and far apart for the wide ones.

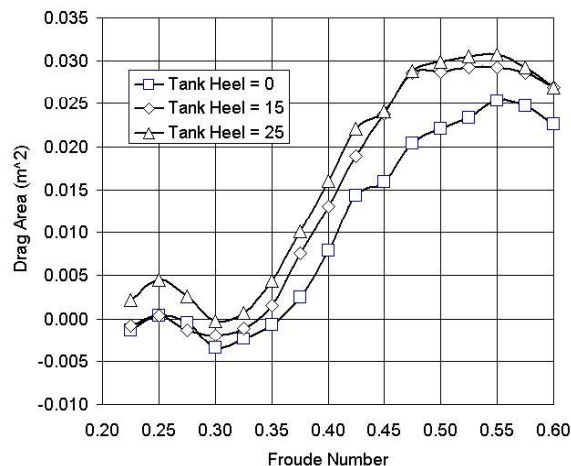


Figure 25 – Model 4 Appendage Residuary Resistance

Figures 19 through 25 show that the residuary resistance of sailboats, when heeled, is fairly complex in its variations, particularly across boat speed. We offer the following observations:

1. The ratio of heeled to upright drag can probably best be represented by a worm curve. That curve would start with high values, quickly drop low and then level off.
2. For narrow boats, Models 4 and 7, there is actually very little increase in residuary drag with heel.
3. For wide boats, Models 6 and 9, there is a substantial increase in drag with heel and the curves would level off at values greater than 1.

The result is an apparent discrepancy that punishes boats with wide beam: the IMS rule predicts an increase in residuary resistance with heel that is relatively constant with beam, while the IMD tank data shows that wide boats have a large increase in resistance with heel.

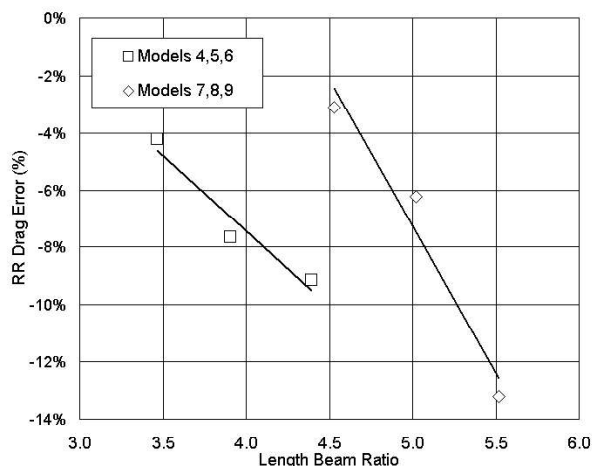


Figure 26 – Heeled Residuary Resistance Error, at $F_n = .4$ and Heel = 25.

Figure 26 shows this more clearly at a heel angle of 25 degrees and Froude number of 4.0. The vertical axis gives the difference in IMS and IMD predictions of heeled residuary resistance, expressed as a %. Negative values imply that IMS over-predicts the drag. The most negative numbers in the two series are at the highest length beam ratios. The wide boats have the least negative numbers and are substantially disfavored.

A more accurate formulation would reduce the prediction of drag due to heel and discriminate between boats that are wide from those that are narrow. This would have two positive effects: bring upwind boat speed predictions more in line with actual performance and eliminate some bias punitive to wide beam.

CONCLUSIONS

The US Sailing tank test program at the Institute for Marine Dynamics has proven to be a valuable tool for expanding our knowledge of the hydrodynamics of sailboat hulls.

Although the program is not yet completed, results of the early tests have already been used to improve the modeling of residuary resistance in the IMS Rule. In addition, analysis of the data taken with the models heeled indicates that there are significant errors in the current IMS predictions for drag due to heel. It is anticipated that these errors will be addressed by the ITC in the near future.

Three more models, the beam series with heavy displacement, are scheduled for testing in 2003. The results of those tests along with analysis of hull effects on induced drag and added resistance in waves will support further development of the IMS Rule.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of the Institute for Marine Dynamics, St. Johns, Newfoundland for their support of this program, the Cruising Club of America for helping to get the program started, US Sailing's McCurdy Fund and the sailors and organizations who have to it, and the US Sailing Foundation.

Much of the work described in this paper is just the continuation of decades of efforts of dedicated volunteers who are greatly responsible for the successes of sailing yacht handicap rules.

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Kerwin, J., "A Velocity Prediction Program for Ocean Racing Yachts Revised to June 1978", MIT/H. Irving Pratt Ocean Race Handicapping Project Report 78-11, July 1978.

APPENDIX

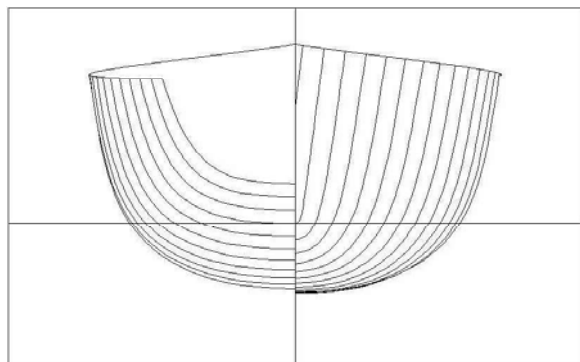


Figure 27 – Model 4 Lines

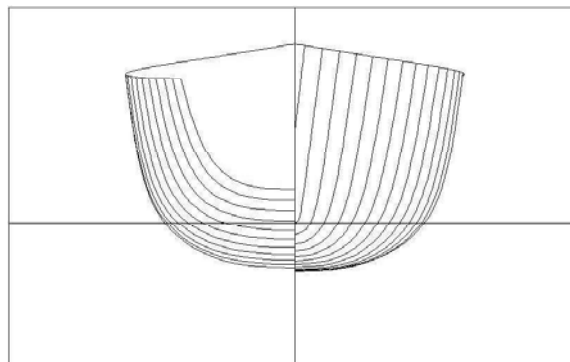


Figure 30 – Model 7 Lines

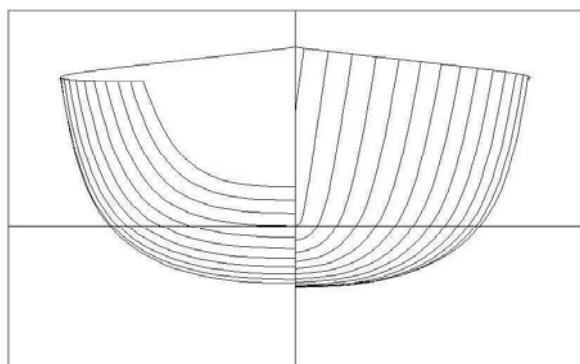


Figure 28 – Model 5 Lines

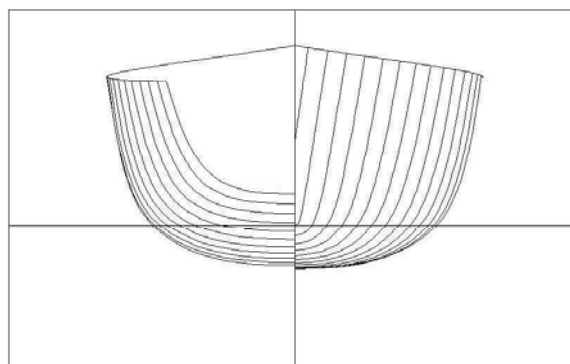


Figure 31 – Model 8 Lines

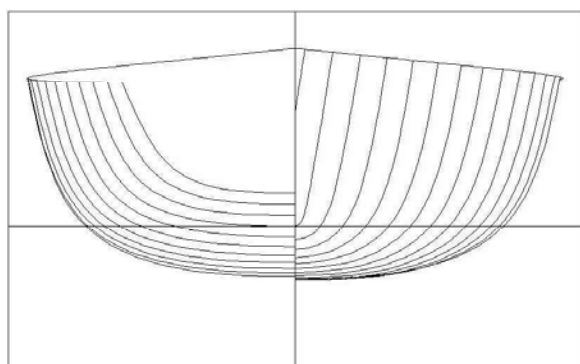


Figure 29 – Model 6 Lines

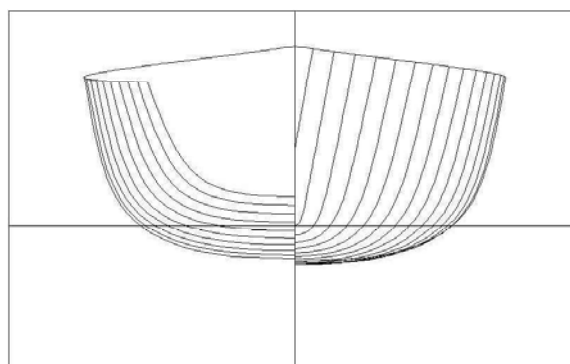


Figure 32 – Model 9 Lines