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Teeters, James; Pallard, Robert; Muselet, C.

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Win, place or show – how deep does your rudder go?

James Teeters

Robert Pallard

Caroline Muselet

Teeters, Pallard and Muselet reveal some of the science behind the complex world of international yacht handicapping.

Who Should Read this Paper?

High profile events such as the America's Cup attract a significant amount of interest from both the sailing community and the general public. This paper illustrates the importance of science and technology to this high profile sport. Yacht designers, builders and owners will all have an interest in the results. The former because they now have more accurate information on which to base design and build decisions to the benefit of boat owners. The latter because they can use the results to help them make informed decisions on the tradeoffs between deep and shallow draft rudders on cruising and racing yachts.

Why it is Important

The primary focus of the paper was to investigate how the draft of rudders affects the performance of sailing yachts. The results reveal the benefits of deep draft and quantify, for one model that is typical of racing sailboats, what those benefits are for different points of sail in different conditions.

The clearest benefit to the international yacht racing community is that a significant performance factor has now being assessed using a rational methodology. This promises to close a loophole in the rating rules that provided an unfair advantage to boats with very deep draft rudders.

About the Authors

James Teeters holds an M.S. in ocean engineering and is presently Associate Offshore Director for US SAILING, the national governing body for sailing in the US. He is also president of the Sailing Yacht Research Foundation, and a yacht designer with Langan Design Associates.

Robert Pallard is a Technical Officer at the Institute for Ocean Technology. His area of expertise is physical modeling of ships and yachts. He has been a part of four America's Cup teams over the past 14 years and will be managing the tank program for Alinghi for the 33rd Defense of the America's Cup.

Caroline Muselet is a Research Officer at the Institute for Ocean Technology. Her area of expertise is naval hydrodynamics, with a focus on tank testing of sailboats. She was the technical authority for the tank testing program of Alinghi for both their 2003 Challenge and their 2007 Defence of the America's Cup.

Analysis of Rudder Span Effects on IMS Hydrodynamic Induced Drag

Teeters, James[1]; Pallard, Rob[2]; Muselet, Caroline[3]

1. Associate Offshore Director, US Sailing, P.O. Box 1260, 15 Maritime Drive, Portsmouth, RI 02871-0907 Phone 1-800-USSAIL1; Fax: 401-683-0840; e: Jim@tytech.org
2. Technical Officer, Institute for Ocean Technology, Arctic Avenue, St. John's, NL, A1B 3T5, Phone: 709-772-4295; Fax: 709-772-2462; e: Rob.Pallard@NRC-CNRC.GC.CA
3. Research Officer, Institute for Ocean Technology, Arctic Avenue, St. John's, NL, A1B3T5; Phone: 709-772-4913; Fax: 709-772-2462; e: Caroline.Muselet@NRC-CNRC.GC.CA

ABSTRACT

The physical draft of keels has long been known to be critical for the upwind performance of sailboats and has long been an element of handicap rules. The IMS rule uses a relatively sophisticated algorithm for assessing keel draft yet, as is the case with other rules, has never included any influence of rudder span. However, there is considerable empirical evidence that rudders can make a significant contribution to performance by increasing the total effective draft. Tank test research was conducted to explore rudder span and quantify performance differences. The results have been incorporated into the IMS rule in a way that is intended to give some rating relief to boats with shallow rudders, yet not drive optimised design in that direction.

NOMENCLATURE

ρ	Density of water
G	Gravity
Lwl	Waterline length
Bwl	Waterline beam
V	Boat speed
Leeway	Angle of attack of boat centreline to flow
Yaw	(Leeway)
Heel	Angle of roll of boat about centreline
δrudr	Angle of deflection of rudder
Fr	Froude number, non-dimensional speed = V/(G * Lwl)^.5
Q	Dynamic pressure = 1/2ρV^2
CE	Center of effort
Karea	Keel profile area
Rarea	Rudder profile area
dCl/dA	Lift slope (lift coefficient per radian)

INTRODUCTION

IMS HANDICAPPING

The International Measurement System (IMS) rule has been handicapping racing sailboats since the late 1970s through its precursor the MHS rule. The heart of the rule is the estimation of boat speeds using a Velocity Prediction Program (VPP). The VPP uses representations of the fundamental science of sailboats and resolves the balance of forces and moments of static equilibrium.

The purpose of the IMS VPP is to provide sufficiently accurate estimates of speed differences between various sailing boats, at various conditions of wind and course, to derive handicaps or time allowances to enable those boats to race equitably. This is, of course, a goal of virtually all rating rules. VPP based rules are unique in that they rely almost entirely on scientific methods.

Contrary to many VPPs, such as those often used in America's Cup campaigns, the IMS VPP generates its own prediction of the hydrodynamic and aerodynamics characteristics of the boat and rig in question. A system of algorithms, originally shown by Kerwin [1978] with updates well documented by Claughton [1999], has been developed to represent the data generated by research. These algorithms require boat measurement. Hulls, keels and rudders are "wanded" with a device that generates a family of transverse curves from bow to stern. Rigs are measured, as well as the dimensions of the sails. The boats are floated in water where freeboards are taken and the stability derived from an inclining test.

The importance of high quality scientific data to such a rating system is obvious. The rule is only as good as the underlying data and the algorithms that represent that data. Systematic research, such as tank testing of hulls and wind tunnel evaluations of sails, is conducted as part of ongoing rule development.

RUDDER SPAN

Over the course of the last decade, yacht designs optimised to the IMS rule have developed deep rudders in parallel with deep keels. Yet, as of the 2001 version of the rule, there had never been any performance assessment of rudder span.

Boat racing is the full scale-testing venue that provides the ultimate evaluation of what is fast. If something is successful on the racecourse then there is likely a good reason for it.

As rudders became deeper and developed ever higher aspect ratios, it became apparent to the IMS rule makers that this is something we may want to handicap, not to penalize deep draft but to give some rating relief to boats with shallow rudders. This is in keeping with the IMS philosophy of seeking to handicap diversity without driving design into specific solutions. In other words, we did not want owners of boats with shallow rudders to feel compelled to replace them. At the same time we did not want to penalize deep rudders to the extent that owners would be compelled to use shallower ones.

The viscous drag effects of rudder area and aspect ratio are reasonably well accounted for in the IMS VPP. The obvious source of the unrated performance benefit was the reduction of induced drag.

LIFT-INDUCED DRAG

Lift induced vortex drag is created whenever a device of limited span, such as the wing of an airplane or the keel (rudder) of a boat, generates lift. This occurs in practice when the device, or foil, is placed in an onset flow at an angle of attack to that flow. Lift can also occur at zero angle of attack if the foil is asymmetric in shape, such as a cambered wing. Induced drag is the consequence of shedding vortices at the tip of the foil. This tip vortex can be observed using flow visualization techniques. Figure 1 is a photo, from behind, of a keel and bulb configuration taken at the Glenn L. Martin Wind Tunnel, University of Maryland. The white oil film clearly shows the spiralling of streamlines around the black bulb. The energy that goes into creating this tip vortex is the source of the induced drag.

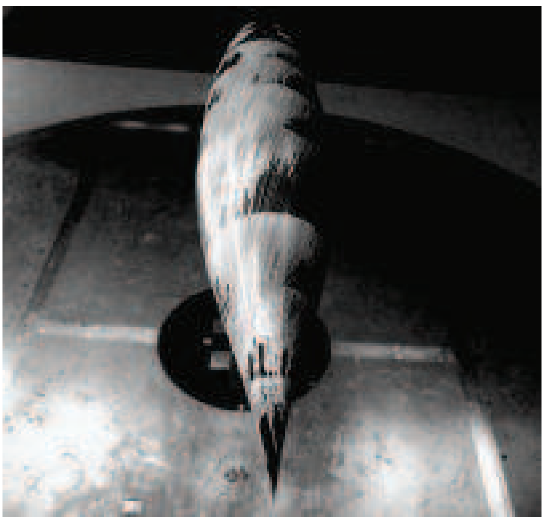

Figure 1. Flow Visualization of Tip Vortex on a Keel/Bulb

Span is certainly the most critical element of foil geometry effecting how much induced drag is created for a given lift. For a sailboat this span is the physical draft of the keel below the water surface. The IMS VPP uses this draft to calculate the lift-induced drag. The formula is relatively sophisticated in that it includes the effects of hull beam/draft ratio with a conformal mapping method, along with heel angle and boat speed factors derived from a variety of sailboat tank programs.

TANK TEST PROGRAM

The International Technical Committee (ITC) of the Offshore Racing Council (ORC) committed to a research and development program investigating rudder span for incorporation into the IMS rule.

US Sailing already had an ongoing tank test program with the Institute for Ocean Technology (IOT) in St. John's, Newfoundland. The principal focus of this program has been systematic variations of canoe body beam and displacement, appended and bare, in both calm water and head seas. The ORC, US Sailing and IOT, as part of the latter's internal research, collaborated on the rudder test program.

The US Sailing baseline model, IMD5, was chosen as the test hull for the rudders. The full scale characteristics of that hull and its keel are shown in Table 1. Test models are ½ scale. The keel is a simple trapezoidal shape.

Lwl (m)	12.465
Bwl (m)	3.193
Hull Disp (m^3)	8.936
Keel Draft (m)	2.955
Keel Span (m)	2.45
Keel Root (m)	1.585
Keel Tip (m)	1.056
Keel T/C	13.00%
Keel LE (% Lwl)	43.30%

Table 1. Hull/Keel Characteristics

RUDDER GEOMETRY AND CONSTRUCTION

To investigate rudder span effects, a family of three rudders was developed. These are illustrated in Figure 2 with characteristics listed in Table 2. There is a regular variation in span and in depth ratio (rudder tip depth to keel tip depth) from the shallow to the deep rudder. A lifting line analysis was used to ensure all three rudders have the same lift slope (lift area per degree angle of attack.)

	Deep	Mid	Shallow
Span (m)	2.8	2.3	1.8
Depth Ratio	0.968	0.796	0.621
Root (m)	0.508	0.660	0.950
Root T/C	18.00%	15.00%	12.00%
Volume (m^3)	0.0591	0.0710	0.0995
Prof Area (m^2)	1.228	1.344	1.602
dCl/dA (/radian)	5.320	4.885	4.074
LiftArea@4deg (m^2)	0.456	0.458	0.456

Table 2. Rudder Characteristics

Along with the span variation, there are variations in rudder volume and the vertical and longitudinal centers of those volumes. This will certainly have some effect on performance. The rudders will also have different frictional drag characteristics. The IMS rule currently has assessments of such effects and the intent of this study was to limit the analysis to changes in induced drag.

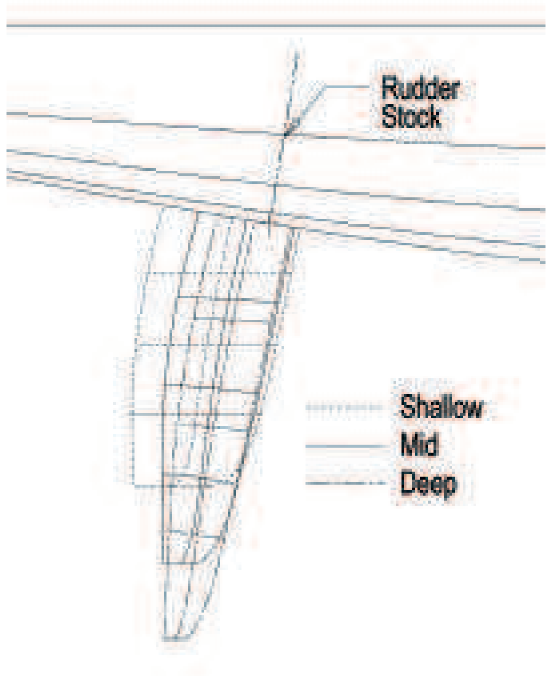

Figure 2. Rudder Profiles

The rudders were milled from Renshape 550 - a high density, fiber reinforced tooling foam with good edge holding characteristics - in the IOT model shop with integral rudder stocks. Figure 3 shows the deep rudder under construction.

Figure 3. Milling of Deep Rudder at IOT

RUDDER TEST MATRIX

The lift required of the hull/keel/rudder configuration on a sailboat is a function of the stability of the boat and its angle of heel. For a given configuration, the lift actually generated is dependent on the parameters of leeway, rudder angle, heel and boat speed. To determine the matrix of variations of these parameters, the IMS VPP was executed with a boat model of IMD5 appended with the mid-span rudder. The cross symbols in Figure 4 show the combinations of heel angle and boat speed, expressed as Froude number, from the VPP. The left hand string of crosses is composed of upwind solutions; the right hand string are reaching solutions.

The circles are the values chosen for tank test analysis. Regular values of heel and speed were chosen to facilitate comparisons. At each of these combinations of heel and speed, a set matrix of 3 leeway and 4 rudder angles was tested. These angles were chosen to bracket the requisite lift, as determined by the VPP. The entire test program for each rudder is shown in Table 3.

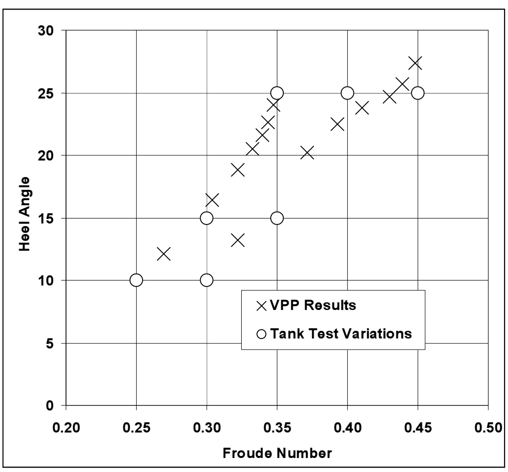

Figure 4. Heel and Speed Variations from IMS VPP

Heel (deg)	Speed (Fr)	Leeway (deg)	Rudder (deg)
10	.25, .30	1.5, 3, 4.5	2, 4, 6, 8
15	.30, .35	1.5, 3, 4.5	2, 4, 6, 8
25	.35, .40, .45	1.5, 3, 4.5	2, 4, 6, 8

Table 3. Test Matrix

TURBULENCE STIMULATION

Previous work had indicated that the turbulence stimulation scheme used in the past for appendages was inadequate. That scheme was to use 3x3 mm cylindrical studs with a spacing of 25 mm at ¼ chord. Their advantage was chiefly that they were readily available and simple to install. Their disadvantage is that they do not trip flow consistently even at the speeds of a large scale tank test and they have relatively high parasitic drag. The inconsistency in the ratio of laminar to turbulent flow on the foil results in higher uncertainty in the measurement of drag.

Tests in wind tunnels are typically done at much higher Reynold’s number than can be achieved in a towing tank which simplifies the turbulence stimulation scheme as the thickness of the laminar boundary is much thinner and the size of the disturbance necessary to trip the flow is much smaller and, hence, its parasitic drag can generally be ignored.

For this test, information for sizing of turbulence stimulation in wind tunnels was used to design a scheme that would work in the Reynold’s number regime experienced in a towing tank experiment. The height of the trip needs to be set for the lowest speed for which reliable drag measurements are needed. This means that at the higher speeds of the test there will be parasitic drag due to the turbulence stimulation and having a relatively easy way of quantifying this effect is desirable. Figure 5 is an infrared image of a rudder in a wind tunnel showing the transition from laminar to turbulent flow at the trip location.

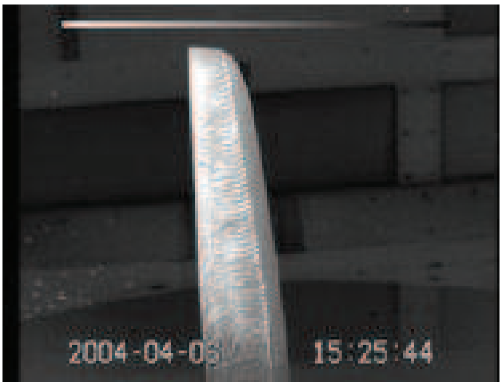

Figure 5. Transition at Trip Location

Figure 6 shows the relationship between the trip height used for these tests and the Blasius estimate of the thickness of the laminar boundary layer.

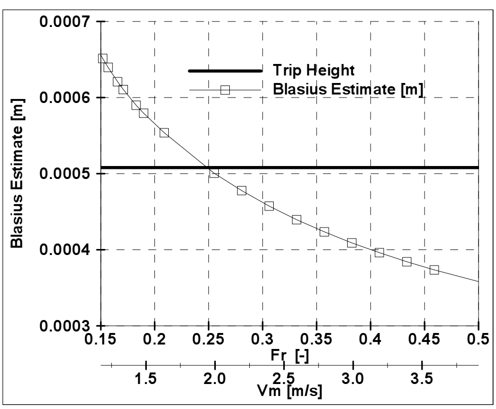

Figure 6: Boundary Layer Thickness and Trip Height

TANK TEST RESULTS

LIFT DRAG POLARS

Figure 7 shows typical results for a given heel angle and boat speed. All data shown is model scale forces with drag corrected for turbulence stimulation. Drag Area (drag/Q) is plotted vs. Lift Area (lift/Q.) The lift being plotted is in the horizontal plane, perpendicular to the course through the water. Please note that the drag shown is total, not just lift-induced, drag. The rudder sweeps (2, 4, 6, 8 degrees) at each leeway angle are connected with curves. Because there are 3 rudders and 3 yaw angles, there are 9 curves in total. The leftmost 3 curves are for 1.5 degrees leeway, the rightmost for 4.5 degrees.

A few observations are in order.

- The induced drag here is the difference in drag at a particular lift to the drag at zero lift.
- Induced drag is proportional to lift^2. This is why the curves of the yaw sweeps are essentially parabolic.
- The range of lift generated at this heel and Fr is quite broad. Indeed some of the combinations of leeway and rudder are outside what is normal for a conventional sailboat. Some of these combinations imply dramatic changes in longitudinal center of effort. However, the test matrix, as designed, permits a clear numerical representation of induced drag.

Quite clearly, at a given Lift Area, the Drag Area is substantially reduced with increasing rudder span.

This is the performance benefit currently ignored in handicap rules.

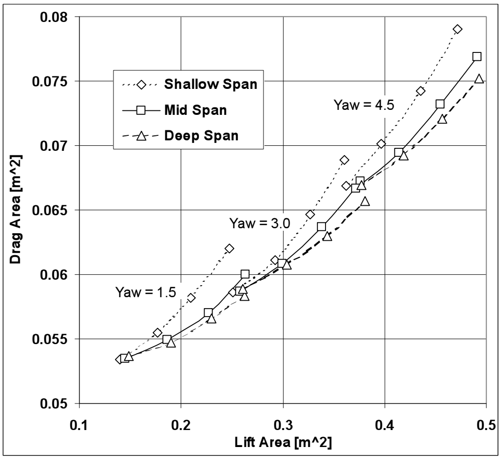

Figure 7: Lift and Drag at Heel=15, Fr=.345

LONGITUDINAL CENTER OF EFFORT

Figure 8 illustrates the effect on the longitudinal center of effort of the various leeway/rudder combinations. This figure is the same as Figure 7 except that the curves of CE location for the mid span rudder have been added for each leeway. The leftmost curve, 1.5 degrees leeway, demonstrates a large variation in CE depending on the relative loading of keel and rudder: the keel is lightly loaded so a variation in rudder load has a strong influence on the CE. A 2 degree rudder angle creates a CE at about 44% of LWL aft, while an 8 degree angle is at 67%, as shift of 23%.

The hydrodynamic longitudinal center of effort must, of course, balance the aerodynamic center for straight-line sailing. Any imbalance, intentional or not, will turn the boat. In order to derive meaningful comparisons of the rudders it is necessary to constrain the combinations of leeway and rudder angle to ensure realistic values for the hydrodynamic center.

For the purpose of this study, a typical aerodynamic center of effort was imposed as a CE constraint. For example, at Heel=15 and Fr=0.345, the constrained LCE is at 53% of LWL.

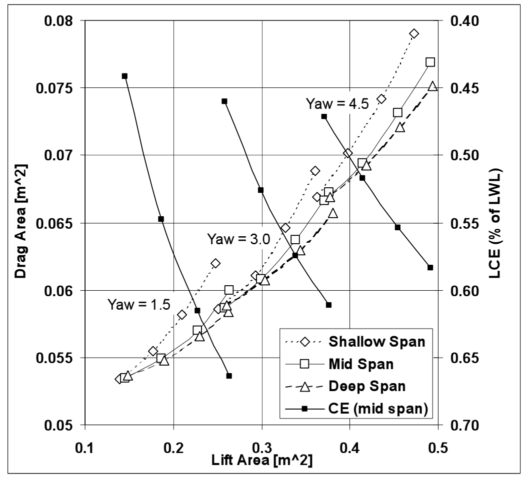

Figure 8: Center of Effort at Heel=15, Fr=0.345

CURVE FITS TO LIFT DRAG POLARS

An effective way to predict the drag, at any given lift for a particular rudder is to formulate an interpolating equation for the data. In this study such numerical fits were performed for each rudder at each combination of heel and speed. Lift and induced drag tend to be represented quite well by simple formulas in which lift is proportional to the angle of attack of a foil and induced drag is proportional to the square of the lift. These relationships suggested the following formulas:

$$\text{Lift Area} = LAkeel + LArudr + LA0 \quad (1)$$

Where

Lift Area = Lift/Q

LAkeel = LSkeel X Yaw X Karea (2)

LArudr = LSrudr X (Ydw X Yaw + δrudr) X Rarea (3)

LA0 represents Lift Area when Yaw = δrudr = 0. LSkeel and LSrudr are coefficients to be determined, along with LA0 and Ydw. LA0 is determined by extrapolating linearly back to δrudr = 0 for each leeway and then extrapolating linearly back to Yaw = 0. Ydw is a factor on Yaw to represent the flow angle at the rudder when the boat is at a non-zero leeway angle. In fact, this factor was virtually 1.0 for all the data sets.

Drag Area = DAkeel + DArudr + DA0 (4)

Where

Drag Area = Drag/Q

DAkeel = C1k X LAkeel^2 + C2k X LAkeel^2 (5)

DArudr = C1r X LArudr + C2r X LArudr^2 (6)

DA0 represents Drag Area when Yaw = δrudr =0.

C1k, C2k, C1r, and C2r are coefficients to be determined along with DA0. DA0 is determined in a similar manner to LA0 except that parabolas are fitted to the data. DAkeel and DArudr represent induced drag.

Yaw Volume = YVkeel + YVrudr + YV0 (7)

Where

Yaw Volume = Yaw Moment / Q

YVkeel = LAkeel * Xkeel (8)

YVrudr = LArudr * Xrudr (9)

YV0 = Yaw Volume when Yaw = δrudr = 0

The yaw moment is used to calculate the hydrodynamic longitudinal center of effort. Xkeel and Xrudr are the centers for the keel and rudder respectively. These can be estimated or determined from a regression method. In this study the latter was performed. The resulting positions were reasonable and consistent across all data sets.

Best fit methods were applied to the data for each rudder at each heel/speed combination. These fits could then be evaluated at any specified lift to find the leeway and rudder angles that resulted in the least drag. Figure 9 shows the minimum Drag Area at each Lift Area for the data in Figure 7. This permits a direct comparison of the drag penalty for reducing rudder span.

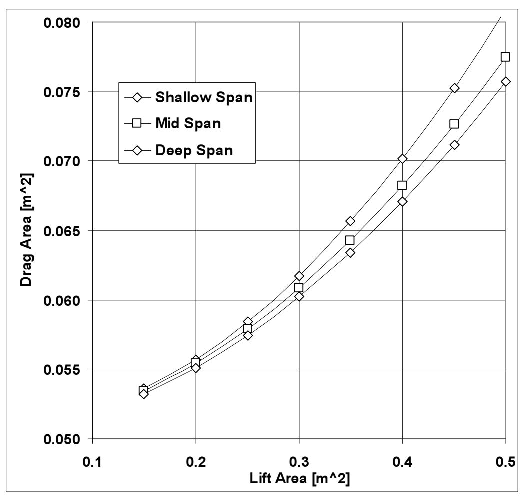

Figure 9: Minimum Drag, Unconstrained CE

CE CONSTRAINED SOLUTIONS FOR MINIMUM DRAG

So far, no hydrodynamic center of effort constraint has been imposed and the results in Figure 9 are, therefore, somewhat optimistic.

Figure 10 shows, for the shallow span rudder, the leeway and rudder angle combinations that produce a requisite Lift Area with the least Drag Area. The solid curves are the results when there is no center of effort constraint, dashed curves with the constraint. For example, a Lift Area of .3 is achieved with a leeway of 3.5 degrees and a rudder of 2.4 degrees. When the CE constraint is imposed, 53% of LWL, the solution leeway is now 2.9 degrees and the rudder 5 degrees. There is a large difference in the solution rudder angles. When unconstrained, the rudder takes on values that are quite a bit lower and CE's too far forward.

The change in angles at the higher lift areas is due to a different constraint: that the leeway angle be less than 5 degrees (the highest angle tested was 4.5 degrees). These higher lift areas would apply to high load situations such as accelerating out of a tack or off the starting line.

Finally, Figure 11 shows the difference in minimum drag, with and without CE constraints, for Heel = 15, Fr = .345. For the shallow span rudder, the difference in total drag is on the order of 1%, for the midspan it is negligible, and for the deep rudder about .3%.

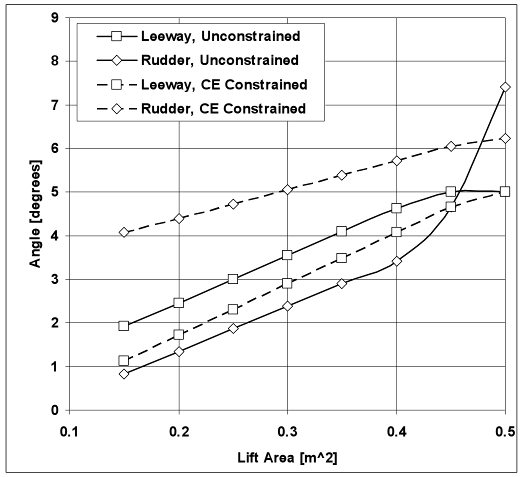

Figure 10: Leeway and Rudder Angles, Shallow Span Rudder, Heel=15, Fr=.345

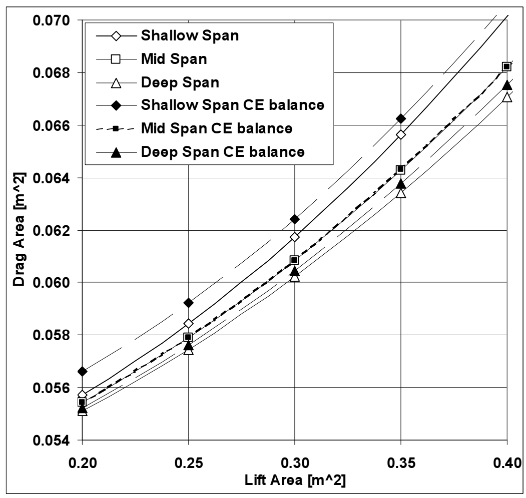

Figure 11: Minimum Drag, Effect of CE Balance at Heel=15 , Fr=0.345

The discrepancy between solutions for minimum induced drag and reasonable yaw balance becomes quite dramatic at very high heel angles and high speeds. Figure 12 shows results for 25 degrees heel, Fr = .45. This corresponds to a sailing condition close reaching at high speeds in a substantial breeze. The minimum drag at a Lift Area of .3 would be achieved, particularly for the deep rudder, with a relatively low leeway and very high rudder angle.

Because of this interesting behaviour, the rudder sweeps were extended by adding a 10 degree setting. The curve labelled "Minimum Drag" passes through the data for maximum rudder angles. At a lift area of .30 the leeway angle is 2.8 degrees and the hydrodynamic center of effort is about 10% of the waterline further aft than what might be called typical. To balance this would require moving the rig substantially aft.

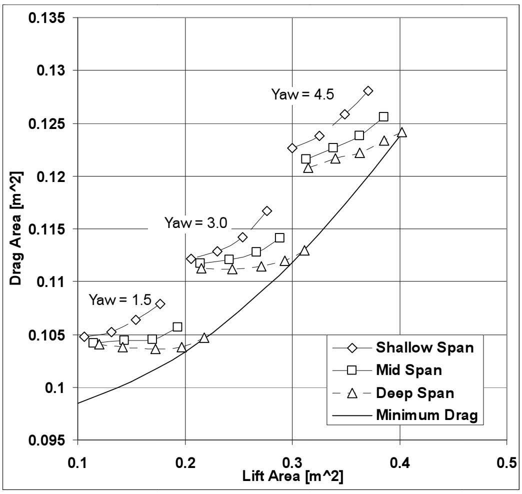

Figure 12: Lift and Drag at Heel=25, Fr=.45

The data for all 7 combinations of heel and rudder has been fit to equations (1) through (9), with a reasonable set of CE constraints imposed. This permitted a realistic comparison of the best potential performance of the various rudders.

IMS RULE DEVELOPMENT

INDUCED DRAG COMPARISONS

Formulas (4), (5) and (6) give the total drag at a given lift. DAkeel and DArudr are, nominally, the induced drag. A more accurate derivation of induced drag is to take the total drag of equation (4) and subtract the actual drag at zero lift. This was performed and the results compared against predictions from the IMS rule. Figure 13 shows the total hydrodynamic induced drag for each of the three rudders as well as that predicted by the IMS 2001 rule for all heel/speed combinations.

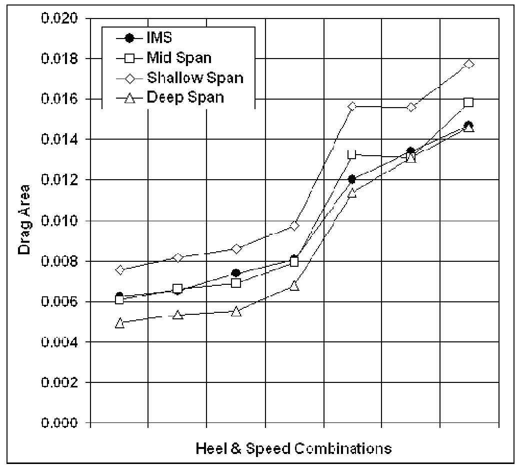

Figure 13: Induced Drag Area at Lift Area = .25

The IMS 2001 induced drag formula (2) was developed in 1993 as a fit to data from a number of tank tests of various keels and hull shapes. It is very encouraging that the VPP predicted drag closely correlates with the "Mid Span" rudder configuration. The draft of that rudder, relative to the keel draft, is similar to that of the pre-1993 tank models. Equally encouraging results were derived at lift areas of .15, .35 and .45.

EFFECTIVE DRAFT

Differences in induced drag can be expressed as differences in effective draft. In the IMS rule, induced drag is given by:

Induced Drag = (FHW/VS)^2 / (PI*ρ*Deff^2) (10)

Where

FHW = Side Force in Heeled Plane

Deff = Effective Draft

An "economical" way to introduce rudder span effects into the IMS rule was to develop a modifier to Deff. Equation (10) can be inverted to derive Deff as a function of induced drag from equation (4).

Figure 14 shows the ratio of these derived effective drafts to those predicted by IMS versus the ratio of rudder depth to keel depth. The curves shown are for the four tank data conditions that most closely approximate upwind optimal sailing. The lift area in all the cases was .25 m^2. It is clear that the change in effective draft is nearly linear with depth ratio. The deep rudder adds up to 10% to effective draft, the shallow rudder takes away about 10%.

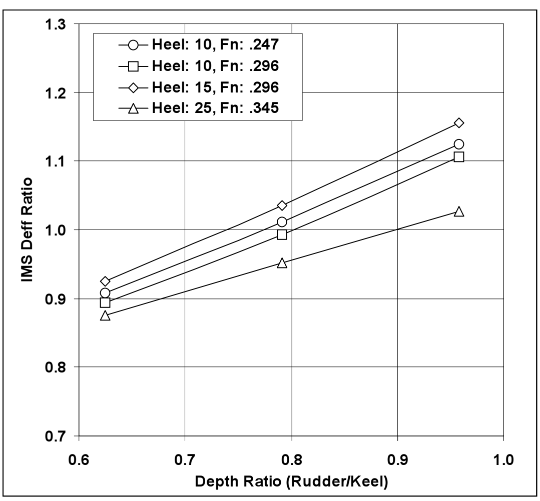

Figure 14: Effective Draft Ratios

A regression was set up to predict the effective draft ratio (EDR) as parabolic in depth ratio (DR) and parabolic in heel angle:

$$EDR = c1 + c2 * Heel + c3 * Heel^2 + c4 * DR + c5 * DR^2 \quad (11)$$

A PHILOSOPHY FOR IMS RULE CHANGES

The requirements of a Velocity Prediction Program (VPP) used for handicapping are not the same as those for a VPP used for design. The former needs to stand up to the intense scrutiny of designers who, quite appropriately, are seeking to design boats that take advantage of perceived biases. Therefore, the algorithms in such a VPP need to be as robust and as simple as possible, yet still faithfully represent the science of sailboats. Algorithms that do not meet those criteria can lead to unreasonable ratings and unfortunate avenues for design exploitation.

Another influence on VPP development is that the success of IMS, just like any rating rule, is measured in part by the size and level of participation of its constituency. Changes to the rule, i.e. VPP changes, are carefully vetted to ensure that they not only provide greater accuracy in ratings, but also do not disenfranchise a significant portion of the racing fleet or steer optimised design into some undesired direction.

So how do you bring changes into the rule without causing unacceptable disruption? One guideline, of long standing, is to give only partial credit for design features that create slow boats. This approach is often called "no credit for towing a bucket." If the rule were to give full credit then it would run the risk of all boats adding "buckets." It is not the intent of IMS to develop slow boats. This "no buckets" philosophy was observed while incorporating rudder span effects.

RUDDER SPAN EFFECTS IN THE IMS RULE

The IMS rule currently handicaps a great diversity of designs with many keel and rudder configurations. There are variations in keel draft to boat length, as well as in rudder draft to keel draft. This particular study had only one ratio of keel draft to boat length. It would take a big leap of faith to believe that the results of this limited tank test program would apply to all the appendage configurations that exist in the IMS fleet.

The ORC therefore adopted a conservative approach that would give some rating relief to boats with shallow rudders, but not enough to drive design towards "requiring" such rudders. Figure 15 shows the same type of data as in Figure 14, this time for a heel of 15 degrees, a Froude number of .296 and three lift areas. Included is a curve entitled "Regression Fit" using equation (11) evaluated at this heel and the tank test depth ratios.

It is important to remember that, for a handicapping rule, the slope of the change in effective draft ratio with depth ratio is more important than the absolute value of effective draft ratio, i.e., what is critical for the IMS VPP is to predict that change in performance with a change in design because relative ratings between boats sort out winners from losers. It would, of course, be nice to have absolute predictions as correct as possible; it just has a lower priority.

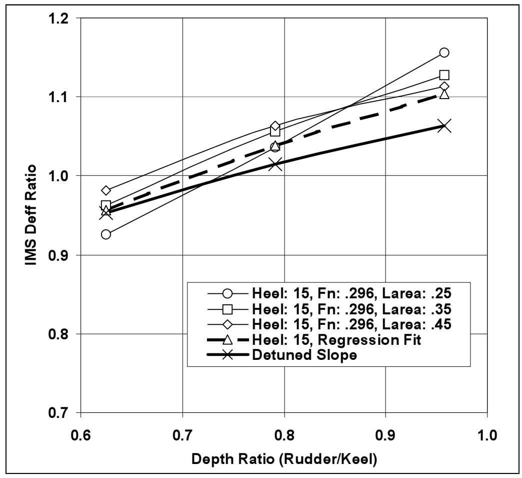

Figure 15: Implied IMS Deff Correction Factor

The last curve in Figure 15, titled "Detuned Slope", is the critical one. This illustrates the assessment of rudder draft that was actually incorporated into the IMS 2002 rule. Note that the slope is shallower - it is actually 75% of the dashed line regression fit. This means that only 75% of the test implied draft credit is being given to shallow rudders. Because induced drag is proportional to effective draft squared, only 56% (.75 X .75) of the induced drag difference is being compensated. This was intentional, following the logic explained two paragraphs earlier.

Note also that the last curve was forced to go through a value of .75. Figure 15 is only one particular example, at 15 degrees heel and a Froude number of .296. After analysing similar graphs at the other conditions tested, it was observed that the effective draft ratios are, on average, equal to one in the proximity of a depth ratio of .75. In fact, the rudder to keel depth ratio of the models used for the pre-existing formulation for induced drag were on the order of .75 so it is not surprising that any adjustment to that formula for a rudder of that depth ratio would have little effect.

The induced drag "credits" derived from this formula, even with the 25% factor, can be quite significant for boats with shallow rudders and relatively deep keels. Consistent with the concerns expressed earlier that only one keel span was tested in this study, a further de-tuning was imposed as a linear function of the ratio of keel depth to hull waterline length. For extremely deep keels, where physical keel draft is 30% of waterline length, there was no further adjustment. For shallow keels that are only 15% of waterline length, only 50% of the credit for effective depth was applied.

The following equations list the entire formula used in the IMS 2002 rule.

AppDepthRatio (ADR) = Rudder Draft / Keel Draft
DraftLengthRatio (DLR) = Keel Draft / Hull Length
DraftLengthFactor (DLF) = 1 - 3.333 * (.3 – DLR)
RudderSpanFactor (RSF) = 1 + DLF * {.75 * .927 * (ADR - .75) + .75 * (-.3056) * (ADR^2 - .75^2)}

Where, in IMS terms:

Rudder Draft = DHRA

Keel Draft = DEF (DHKA + centerboard effects)

Hull Length = LSM1

Figure 16 illustrates these equations. Each curve is for a different keel draft to hull length ratio (DLR above.) The intentional reduction in rating adjustment for boats of shallow draft is clear.

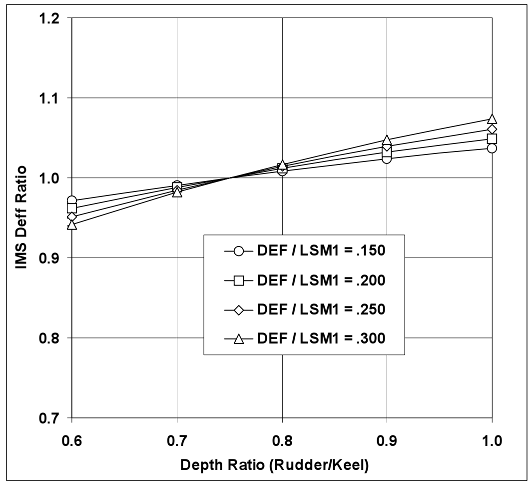

Figure 16: Effect of Keel Depth to Waterline Length

CONCLUSIONS

The ultimate test of any change in a handicapping rule is whether the change promotes better racing. What the ORC has tried to do is:

- Recognise a characteristic of sailboats (rudder draft) whose effect on performance is not assessed and is, therefore, being exploited.
- Conduct research to derive an analytical representation of the performance effect.
- Create a VPP algorithm that gives a reasonable rating assessment without driving optimised design into a new direction, i.e. without forcing owners to alter their boats.

In the case of rudder depth, the test data showed very clear distinctions between the rudders, so drafting a rule algorithm was relatively straightforward. That algorithm was then slightly 'tuned' to give most but not all of the rating credit due to boats with shallow rudders. The maximum change in speed for boats in the ITC test fleet sailing upwind in 12 knots is about +/- 4 seconds per mile, or approximately one boat length per mile. Most boats will be affected by less than one second per mile.

Deep rudders are still somewhat favoured, but only by a small margin. Again, the goal was to provide some rating relief for shallow rudders but not so much that we encourage them and thereby promote slow designs.

It is expected that the induced drag characteristics of a keel and rudder combination could be well represented by the use of biplane theory. Indeed the IMS rule does this to handicap ketch and yawl rigs. Applying biplane theory to keels and rudders could provide a logical, technically defensible, method to handicap a greater variety of appendage combinations. Much of the change in induced drag seen in this study, particularly at high speeds, could be the result of deformation of the free surface. The results presented in this paper would be necessary to “calibrate” the biplane algorithms.

Aside from IMS handicapping considerations, it is clear that there is quite a bit of variation in optimal leeway and rudder angles that, depending on heel angle and boat speed, provide minimum drag. It is interesting to speculate on the development of a rig and sailplan with sufficient fore and aft flexibility to realize the potential reductions in hydrodynamic induced drag.

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Lastly, we would like to thank all the “rule technicians” who precede us that have been interested in and volunteered enormous energy to the science of handicapping sailing yachts. Our efforts follow their lead.

REFERENCES

Kerwin, J.E., “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.

Claughton, A., “Developments in the IMS VPP Formulations”, SNAME 14th CSYS, Annapolis, MD, pp 1-20, 1999.