Design Considerations for Canting Keel Yachts.

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1. Introduction.

The emergence of canting keel yachts is one of the more significant developments in sailing yacht design. Since yacht racing began crews have known the advantages of increasing righting moment by hiking, and stacking gear on the weather side of the yacht. The logical extension of this approach was the use of water ballast tanks to provide a more easily managed and less costly way of increasing righting moment. Using water ballast to provide extra righting moment increases the weight of the yacht, so the extra power to carry sail arises as much from the extra displacement as the offset centre of gravity. This is a good thing when sailing upwind, but on reaching courses the extra weight is a handicap.
Canting keels sidestep this problem, now the whole ballast package can be made to "hike out". Because you don't need beam to get water ballast or crew outboard the boats can be made extraordinarily narrow, to such an extent that conventional sailing with the keel on centreline might become problematical, and awkward situations for a conventional yacht such as a "Chinese gybe", have the potential to become major dramas with the keel helping to heel the boat.
As in all yacht design there is no free lunch, canting the keel takes the major lift producing appendage and increases its effective heel angle to the point where it become redundant in resisting the heeling force from the sails. Thus many canting keel yachts are obliged to fit a forward rudder or dagger board to take on the role of the keel.
This type boat is so different from the norm that the tools for designing them, and the safety regulations to which they are subjected have had to be updated.
This paper describes these developments

2. Terminology

This paper will essentially consider 3 type of monohull sailing yachts.

- Conventional yachts with fixed, ballasted keels and a single rudder.
- Water Ballast yachts which have fixed ballasted keels and ballast tanks that may be filled to increase displacement and offset the horizontal centre of gravity from the hull centreline. These yachts are termed "variable ballast yachts".
- Canting keel yachts, which have a ballast bulb mounted on a keel that can be "canted" to windward. The yachts may or may not be fitted with a forward rudder or dagger board. These yachts are termed "moveable ballast yachts".

3. Righting arm curves.

Typical righting arm curves for the 3 types of boat are shown in Figure 1.

Righting Moment (kg.m) = Displacement (kg) $\times$ GZ (m)
where GZ = Righting arm.

The curves in Figure 1 show typical features of the 3 types of yacht.

- The conventional yacht has no righting arm at zero heel, and has a maximum righting arm at a heel angle of approximately 80 degrees, i.e. outside the normal sailing regime of 0-35 degrees.
- The water ballast yacht with a ballast tank full has an angle of list of 10 degrees, the current limit for Open 60 yachts, and in the sailing regime has 40% more GZ than the conventional yacht, but retains a maximum GZ angle above the sailing regime.
- The canting keel yacht has a higher list angle.

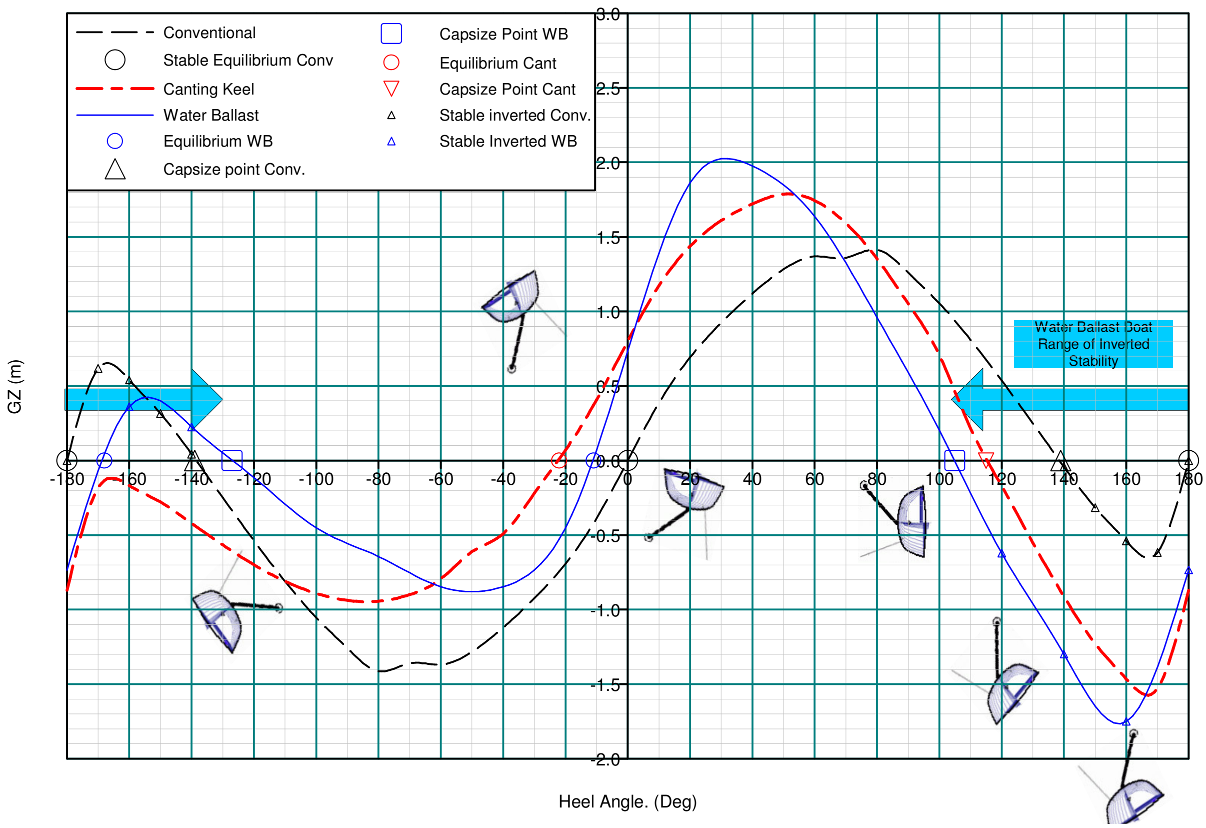


Figure 1. Typical righting arm (GZ) curves.

4. Hydrodynamics

4.1. Total Drag Components.

The equation below shows a convenient way of viewing the calm water resistance of a sailing yacht. The total hydrodynamic drag is assumed to be the sum of the following components:

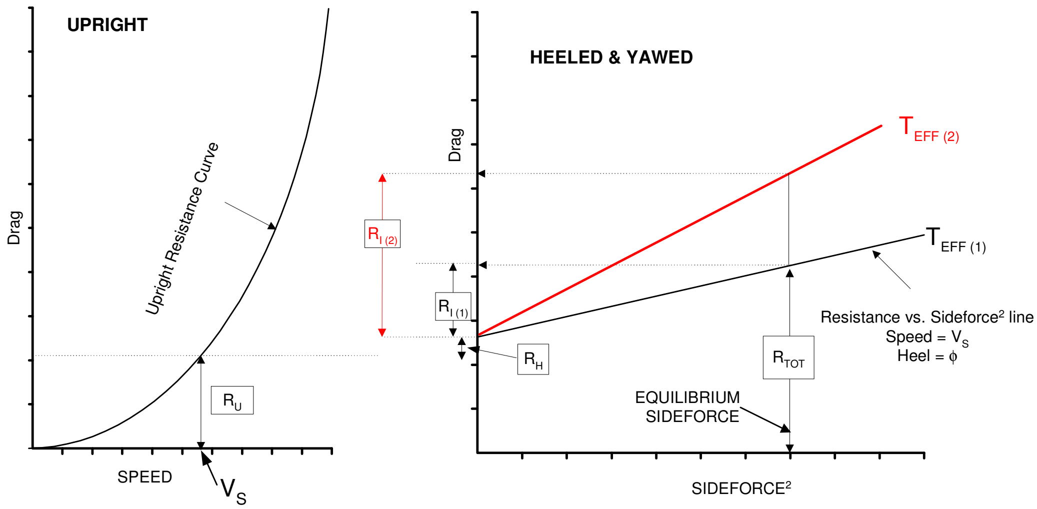
$$R_{TOT} = R_U + R_H + R_I$$

Upright Resistance (R_U) comprising:

Residuary (wavemaking) resistance
Appendage viscous drag
Canoe body viscous drag

Heel drag (drag due to heel alone) (R_H)
Induced drag (R_I)

The combination of R_U, R_H and R_I is shown graphically in Figure 2. At a given speed (V_S) the upright resistance is determined from the resistance curve. When the yacht heels and produces sideforce the resistance value can be determined by the intersection of the resistance against sideforce^2 line with the equilibrium sailing sideforce line.
The induced drag (the drag associated with lift production) of the hull and keel is generally assumed to increase linearly with sideforce^2.
For conventional, moveable and variable ballast yachts the estimation of upright and heeled resistance can be done using existing analytical techniques. Water ballast yachts generally have higher BMAX/BWL (Maximum / Water line beam) ratios and the prediction of heel drag for these shapes is somewhat more complicated than for less flared hull shapes.



$$T_{EFF(1)} = \sqrt{2} \times T_{EFF(2)}$$
$$R_{I(2)} = 2 \times R_{I(1)}$$

Figure 2. Breakdown of drag components for a sailing yacht.

4.2. Induced Drag.

Induced drag is the component of resistance that arises when the hull keel and rudder are producing a heeling force. The predominant source of this drag component is the energy lost to the vortex at the keel tip produced by the equalisation of the pressure and suction forces on opposite sides of the lifting foil.

Conventional yachts

The equation below is based on simple theory for the induced drag of a lifting surface of finite span.

$$R_I = {F_H}^2 \Big/ \pi \rho V^2 T_{EFF}^2 \qquad \text{Equation (1)}$$

F_H = Heeling Force, R_I = Induced Drag, T_{EFF} = Effective Draft.

The value of the effective draft (T_{EFF}) is of the same order as total draft. The red line in Figure 2 ($T_{EFF(2)}$) shows the effect on total drag of reducing the effective draft by 40%, i.e. the induced drag is doubled.
If the yacht sailed in a homogeneous fluid then T_{EFF} in equation 1 would be constant. However because of the air – water interface both speed and heel angle affect the value of effective draft. As the yacht sails faster the mid-ship wave trough deepens, and as the yacht heels the root of the keel and rudder move closer to the free surface. Both of these effects allow the pressure field on the keel to produce surface waves, or at worst ventilation, particularly at the rudder root.
These effects mean that the water surface acts less and less as a reflection plane as speed and heel angle increase.

Canting Keels

Canting keels introduce a further level of complexity in that as the keel cants more lift is directed vertically, rather than horizontally, where it can resist the sideforce from the sails. Figure 3 presents some results for a canting keel configuration. The data are presented as effective draft values, non dimensionalised with respect to the geometric maximum draft, for the following conditions.

Condition.	**Heel angle**	**Legend in Figure 3**
Zero cant angle (K=0)	0, 15 & 25 degrees	K=0
40 degree Cant Angle with centreline Dagger board.	0,15 & 25 degrees	K=40 +DB
40 degree Cant Angle without centreline Dagger board.	0, 15 & 20 degrees	K=40

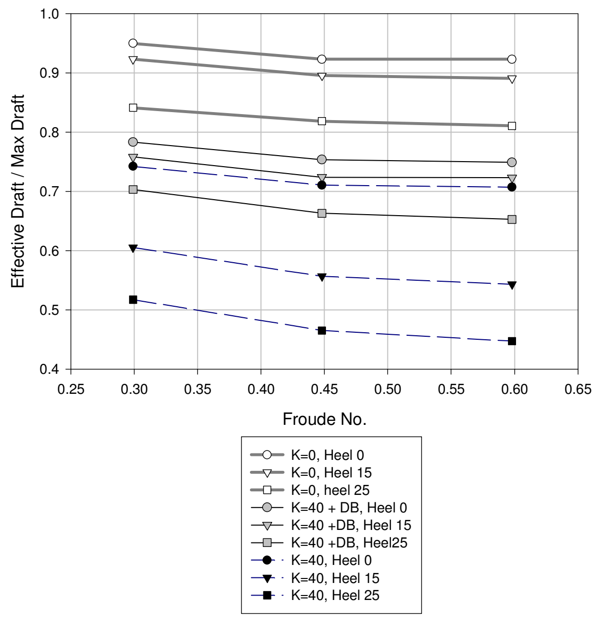


Figure 3. Effective Draft values for various Canting Keel Configurations.

The results show the following trends:

- In the zero cant configuration, i.e. a conventional arrangement effective draft reduces with increasing heel angle and increasing speed.
- Canting the keel reduces the effective draft still further, to the extent that at 15-20 degrees of heel the effective draft is insufficiently high to permit adequate windward sailing performance.
- Adding a centreline dagger board recovers the effective draft to zero cant angle levels, but of course the yacht must now bear the extra wetted surface of the dagger board.

5. Performance prediction.

Figure 4 shows righting moment curves for the 3 types of yacht under discussion. The canting keel curve is for a contemporary racing yacht. The nature of the righting moment curves shown in Figure 4 curves goes some way to explaining the difference in performance that can be realised by the different ballasting arrangements.

Consider that each of the yachts might support the same sail area, and thus will require the same righting moment for similar performance sailing upwind. Thus the conventional boat would require an increase in displacement in inverse proportion to the GZ differences.

Yacht Type	GZ @ 20 deg (m)	Displ. (kg)	RM (kg.m)
Conventional	0.7	10	7
Water Ballast	1.27	5.5	7
Canting Keel	1.7	4.1	7

If displacement is taken as a crude measure of wavemaking resistance then these results show how the augmented righting moment can alter the design to reduce displacement and with it the wave making resistance.

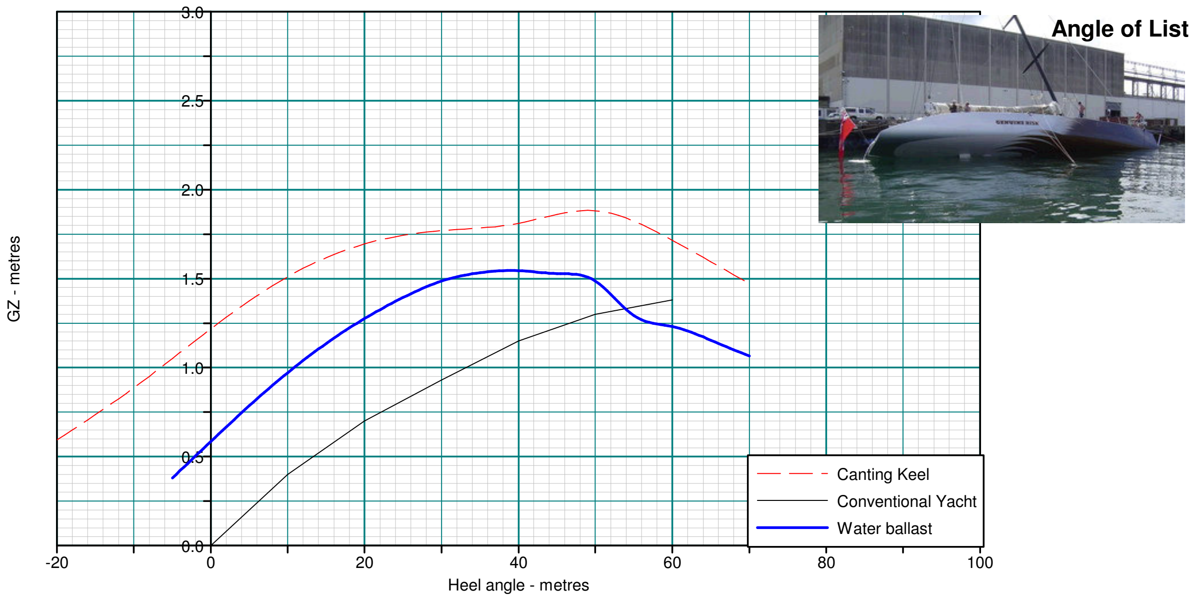


Figure 4. Righting arm curves for contemporary racing yachts.

5.1. Induced Drag

For preliminary design purposes the effective draft of yachts with canted keels can reasonable be assumed to relate to the draft of the deepest appendage, i.e. the draft of the keel until the cant angle is sufficiently large that the rudder of dagger board become the deepest foil. For yachts with high cant angles and a forward dagger board a potential benefit is the reduction of induced drag.
The appendage configuration of a conventional boat is characterised by two lifting surfaces, the fin and the rudder. The sailing appendage configuration for a canted keel may include one of the following appendages:

- Single Centreline Dagger board (possibly with adjustable angle of attack)
- Off-Centreline Dagger board (possibly cambered)
- Forward rudder in addition to aft rudder

In combination with the fin, these configurations appear to have three lifting surfaces. For this discussion, we will state that the most efficient set-up is to unload a highly canted fin and that the canted keel configuration, like the conventional configuration, is actually a two-lifting surface system.

It should be noted that various other treatments could be considered to avoid adding the dagger board or forward rudder. A trim tab on the fin can be considered in lieu of an additional appendage. A tab on the canted keel fin will reduce leeway without the parasite drag penalty of the dagger board. However, it carries the adverse consequence of additional heeling moment. Most importantly, at high heel angles with a large cant angle, in unsteady wind and waves, the boat could momentarily find itself in the unfortunate situation of having no lateral area.

Some have considered large wings on the bulb in lieu of the dagger board. This is difficult to make work in that the winglets are not the most efficient way of increasing lift curve slope, and they are relatively high drag appendages when compared with comparable dagger board area. For cruising boats with canting keels, there are perhaps several moveable “winglet” type systems that should be considered.

In this case we will limit our analysis of these various configurations to that of an elementary system of two interfering lifting surfaces. The performance of this system will depend on the sharing of load between the surfaces, attempting to minimise induced and parasite drag, and satisfying the requirement for balance (in yaw), and directional stability.

Here we can look at the induced drag of these multiple surface configurations on the basis of Prandtl's relation for induced drag of a biplane in potential flow (Ref. 1). Munk's stagger theorem allows us to consider our fin and rudder, or our dagger board and rudder as the two wings of the biplane. The term *stagger (s)* is the longitudinal distance between the two surfaces. For a conventional aeroplane the *gap (g)* is the vertical distance between the wing and the tail, and adjusted by the downwash line of the wing's circulation vortices. For a yacht, we might evaluate the gap as:

$$g = s \times \sin(\lambda - \text{ keel downwash angle})$$

First consider the conventional configuration of keel and rudder. The span of the keel (b_1) is greater than the span of the rudder (b_2). In ideal potential flow, if both surfaces have elliptical loading, then the induced drag is given by

$$D_I = \frac{\dfrac{L_1^2}{b_1^{\,2}} + \sigma \dfrac{L_1 L_2}{b_1 b_2} + \dfrac{L_2^{\,2}}{b_2^{\,2}}}{2\pi q} \qquad \text{Equation 2}$$

Where σ is the interference factor that depends on the span ratio (b_2/b_1) and gap. When the gap is zero, $\sigma = b_2/b_1$ and when the gap is infinite $\sigma = 0$. L_1 is the lift on the deeper forward appendage (typically fin keel), and L_2 is the load on the rudder.
Using equation 2, figure 5 shows how induced drag varies with rudder loading compared to induced drag of yacht where all the side force is carried on the keel only (monoplane.) Shown are three ratios of rudder span to keel span, b_2/b_1 = 0.6, 0.8 and 1.0, for two gap ratios g/b_1 = 0.0 and 0.05.

In Figure 5, the solid lines show the relationship for no gap, and the dashed lines are for gap ratio of 0.05. A gap ratio of 0.05 equates to a value of approximately 1 degree of leeway minus upwash on a typical race boat.

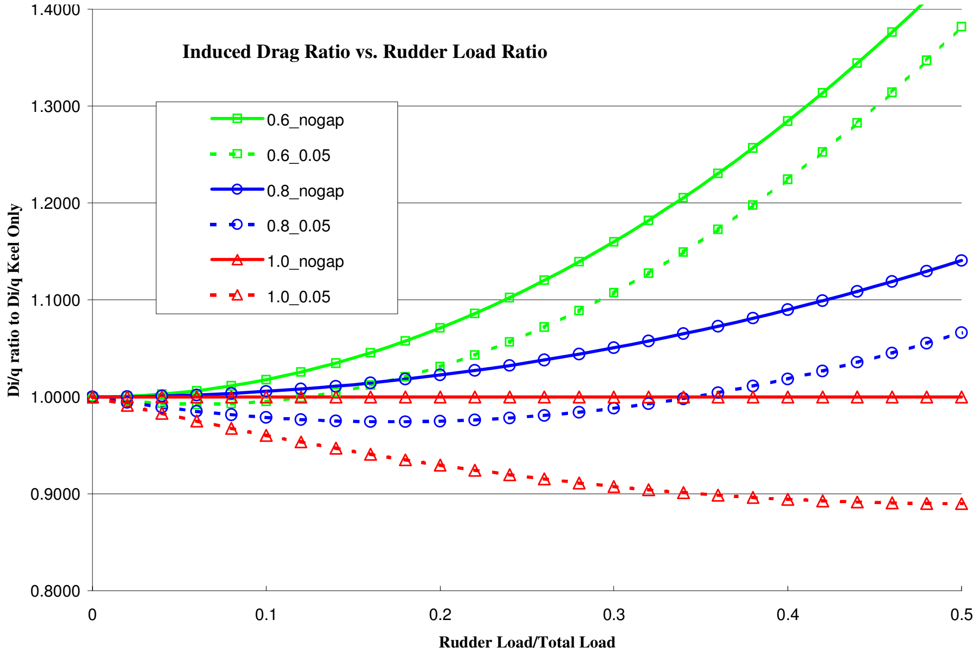


Figure 5. Variation of induced drag with rudder load fraction for three span ratios (0.6, 0.8, 1.0) for gap ratio of 0.0 and 0.05.

A gap ratio of 0.05 is approximately equal to 1 degree leeway for a typical yacht.

From Figure 5 we can make several general observations:

- For a situation where there is no gap, the minimum induced drag occurs with *zero* rudder load. A no gap situation might occur in which leeway is equivalent to keel downwash for example.
- If the effective spans of the rudder and keel are equal, then minimum induced drag for any gap is 50-50 sharing of the load; and for no gap the induced drag doesn't vary with load fraction.
- For a typical rudder-span-to-keel-span ratio, between 0.6 and 0.8, the load fraction for minimum induced drag varies between 0.065 to 0.209. Typical rudder load fractions on a race boat are 0.10 to 0.20.

Let's now look at a range of gap ratio's for rudder-to-keel span ratios of 0.8. Figure 6 shows four curves for gap ratios of 0.05 through 0.20. These are approximately equivalent to leeway-minus-downwash angles of 1 through 4 degrees. We can see for these deep rudders that increasing gap provides the opportunity to reduce induced drag. For minimum induced drag, increasing rudder load is indicated for increasing gap.

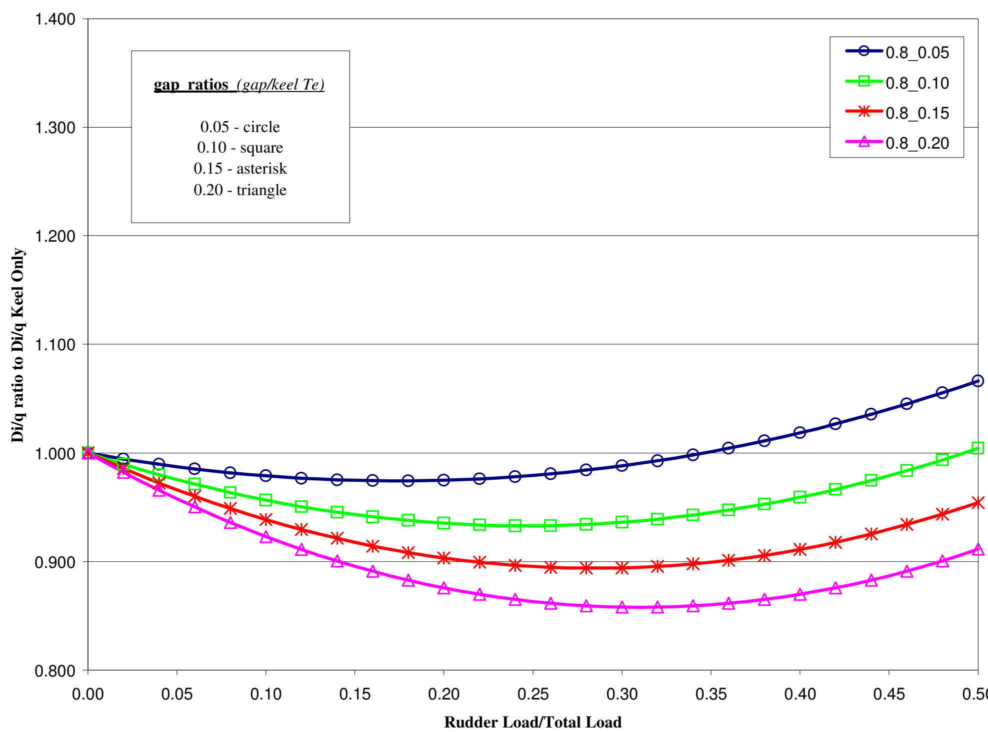


Figure 6. Variation of induced drag with rudder load fraction for various gap ratios at span ratio (b_2/b_1) of 0.8.

Now let's examine what this all means for the typical canting keel configuration. Similarities and differences between conventional configuration and canting keel configuration include the following points:

- If we have a "tacking" centreline dagger board or cambered off-centre dagger boards, the fin will be unloaded, and we are once again considering a staggered biplane similar to the conventional keel, so the previous two figures apply as well.

- The distance between the forward appendage (rudder or dagger board) and the aft rudder will be greater than that of a conventional keel and rudder configuration. This means for the same leeway, we are operating with greater gap ratios than the conventional configuration.
- With canting keel configurations, the span ratio is higher, with b_2/b_1 typically varying from 0.80 to 1.0.
- A cambered or tacking dagger board system, relative to an un-tabbed conventional fin will have less leeway. Leeway in these cases will be a function of side force and rudder angle and might be considered slowly varying relative to the twin rudder configuration.

For a twin forward rudder with aft rudder configuration, leeway is a function of both forward and aft rudder angles. If the forward rudder is just set a fixed angle, then the system operates more like the centreline dagger board with an angle of attack. If the forward rudder is steered rather than fixed, then the leeway and load ratio's can vary quickly over a wider range of angles. With this varying gap and loading ratio, induced drag changes. For the large high performance racing boats with twin rudder systems, the drafts of the rudders are relatively deep so the induced drag in upwind sailing is only 5-7% of the total hydrodynamic drag. Even if gap ratio varies between 0 and .25, this will change the induced drag by about 29%, so the total variation will be about 1.5 % of the total drag.
However, for a yacht with shallower and less efficient twin rudders, the induced drag will be higher and this variation will have a greater effect.

Perhaps most importantly, for a canting keel yacht with two nearly equal-span lifting appendages, there is a conflict between the benefits of reducing leeway, and the reduction in induced drag by increasing gap (through leeway.)

While the biplane equation provides a simple method for evaluating induced drag for two planar wings, there are a number of assumptions which tend to modify the result. A discussion of these assumptions is beyond the scope of this paper, but the include:

- Real rudders and keels are not necessarily elliptically loaded.
- The forward appendage's downwash on the rudder is decreased due to the rollup of the keel (or dagger board) trailing vortex sheet.
- Viscous effects increase the induced drag and interference effects.

Here we have considered induced drag only, to evaluate the total effect of various configurations, it is most practical to use a VPP that provides for canting keels, and considers viscous drag effects, as well as evaluation of load sharing, lift curve slopes and leeway calculations that will provide for the induced drag estimate. To evaluate the effect of placement of various boards or forward rudders on wave resistance, tank testing is perhaps the best measure.

6. Handicapping

In 2004 the Offshore Racing Congress (ORC) was encouraged to adapt the IMS VPP to accommodate moveable and variable ballast yachts. For a software package which was written 20 years ago in Fortran, this was no mean undertaking. As an additional complication the VPP was also required to predict the effect of trim tabs on the speed of a sailing yacht.

The approach adopted was as follows.
Water ballast boats.
The normal afloat measurement procedure was modified to determine the displacement and righting arm curve with and without water ballast. The standard VPP was run twice to determine the best speed on each point of sail, from which a composite speed table was produced.
Canting keel yachts.
The results of the conventional inclining test with the keel fixed on centreline were combined with the list angle produced by the keel at maximum cant angle, to determine the righting moment curve in the canted condition. The complication for the canting keel yacht was how best to determine an effective draft for use in the calculation of induced drag (equation 1).

For IMS the concern was that the formulation might be open to exploitation by designers adopting unusual configurations of keel, rudder and canard. It was feared that these might be rule cheaters that would obsolete the embryonic fleet of canting keel yachts or the existing conventional fleet.
In order to avoid this situation the IMS adopted the following stance.

a) Base effective draft on the deepest draft achievable.
b) Ignore the wetted surface area of the all appendages except the canting keel and rudder.

These "simplifications" ensured that the formulation was hard to exploit and the predicted speeds were much faster than conventional boats.
The strategy worked to such an extent that only a handful of maxi size (90') canting keel yachts were rated in IMS in 2004 and for 2005 the VPP formulation will be amended to ensure that the handicaps align more closely with those of conventional yachts.

The handicapping through VPP calculations presents other difficulties,
Figure 4 shows that for a canting keel yacht the righting arm curve is non linear in the sailing regime, above 10 degrees of heel the curve begins to flatten. This means that making the boat heel more does not produce much extra driving force, consequently optimum heel angles are less than those for conventional yachts.
Canting keel yachts with active forward rudders (CBTF) or yachts with trim tabs on their fixed keels have some independent control of leeway. The associated hydrodynamic and aerodynamic effects are difficult to quantify in a simply implemented handicap system.
The apparent wind angles are generally well forward, modern canting keel yachts are similar to a one hulled catamaran. Apparent wind angles are only wider than 60 degrees in winds over 16 knots and spinnaker poles have been abandoned in favour of bow sprits. This puts into high relief the need for "accurate" sail force coefficients, and it raises issues about sail measurement where the yacht never sets the IMS assumed maximum size sail.

7. Stability regulation.

Current stability regulations for conventional yachts are generally grounded in specifying a required range of positive stability, or a minimum Angle of Vanishing Stability (AVS).
Figure 1 shows a righting arm (GZ) curve for a typical conventional sailing yacht.
The curve is characterised by the following features:

1) Points of stable equilibrium at 0 and 180 degrees of heel.
2) Angle of vanishing stability (AVS) at 139 degrees. This is a "Capsize Point" and heeling beyond this angle the yacht will continue to heel over until it reaches the stable inverted equilibrium position. In the region of inverted stability the curve has triangle symbols added. Any time that the yacht is on this part of the curve it will migrate to the inverted stable equilibrium point.
3) A righting arm of 1.27m. at 90 degrees of heel.

There is a substantial body of regulatory procedures for the evaluation of conventional yachts. All of these are based on the concept of an angle of vanishing stability, which is a measure of how readily a boat may be capsized by wind or wave action. For a conventional yacht the AVS is also measure of the range of inverted stability, and the "stability" of the vessel in the capsized condition, which may be used as a measure of how readily the boat will self right. Research since the 1979 Fastnet Race (Refs 2-4) has demonstrated that whilst wind action may knock and hold a vessel with its rig in the water (Note that the MCA rules have a minimum AVS of 90 degrees even for the largest vessels), it is the impact of a breaking wave that causes vessels to be inverted. Consequently the required AVS reduces as vessel size increases, a reflection that breaking waves are of a fixed size and at large boat sizes you become immune to breaking wave capsize.
This is reflected in Figure 7 where known casualties are plotted on a range of stability (AVS) against. length basis. Also shown on Figure 7 are the various yachts examined by the ORC in their study on safety of moveable and variable ballast yachts.

7.1. Current regulatory regime.

IMS Stability index.

The IMS stability index determines an AVS based on the .OFF file (i.e. no coachroof or cockpit) and calculates a stability index based on AVS modified by the Size Increment (SI) and the Capsize Increment (CI).
Limits for participation in offshore events are based on the Stability Index.

Stability Index. A yacht's eligibility for entry in IMS races of ORC Special Regulations Categories 0, 1 or 2 may be limited by the Notice of Race or Sailing Instructions on the basis of her Stability Index.
The Stability Index minima in the table below are recommended. Because the ORC Race Categories are stated in general terms, the special circumstances of any particular race may make deviations from these recommendations appropriate.

ORC Race Category	Minimum Stability Index
0	120
1	115
2	110

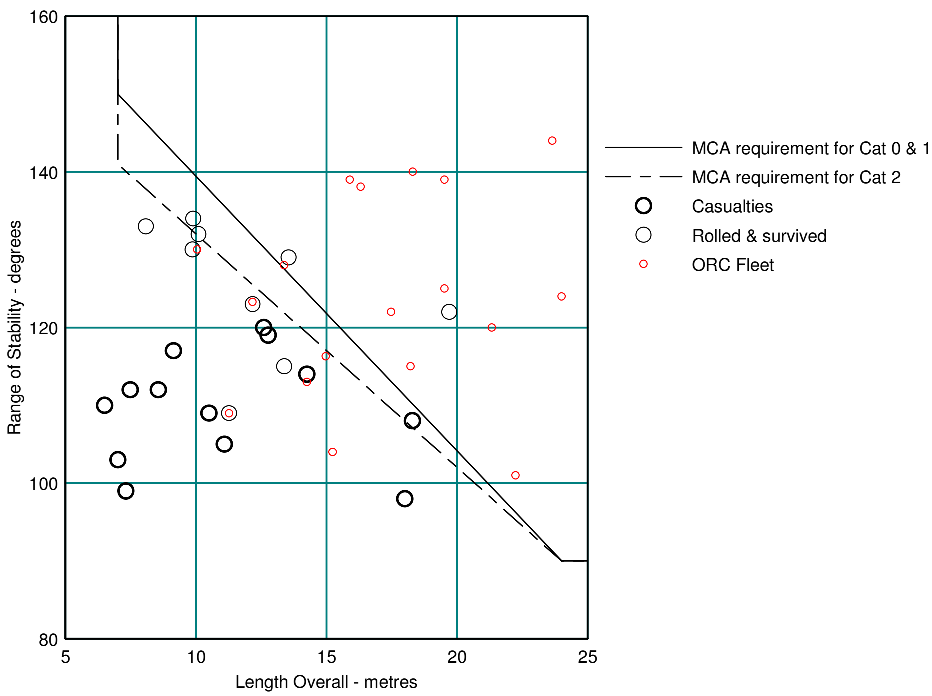


Figure 7. Casualty statistics and MCA range of stability criteria.

ISO Standard. 12217-2

The ISO standard adopts a multi factor approach to determine a stability criterion "STIX"

$STIX = (7+2.25L_{BS})(FDS*FIR*FKR*FDL*FBD*FWM*FDF)^{0.5}+\delta$
L_{BS} = overall length.

The factors are as follows:
Dynamic stability factor (FDS) based on area under the GZ curve as a function of length
Inversion recovery factor (FIR) based on angle of vanishing stability and displacement

Knockdown recovery factor (FKR), is function of the righting moment at 90° and the sail area and centre of effort height

Note that the sail area and CE height are based on mainsail area plus the fore triangle area (IxJ/2).

Displacement-length factor (FDL) benefits the high displacement/length boats

Beam-displacement factor (FBD) function that penalises topside flare

Wind moment factor (FWM) a function of the steady apparent wind speed to heel the boat to the downflooding point.

Downflooding factor (FDF) function of downflooding angle.

δ is an addition factor to credit vessels with a certain level of reserve buoyancy and positive GZ at 90° when flooded

Once a STIX value has been calculated the category for the vessel may be determined based on the table below, which is extracted from the ISO standard.

There is also a minimum AVS for categories A &B based on displacement.

STIX shall be greater than the required value for the design category ($STIX_{(R)}$), as given in Table 5.

Table 5 — Requirements for STIX

Design category	A	B	C	D
STIX shall be greater than $STIX_{(R)}$ =	32	23	14	5

Design category	A	B	C	D
Wave height up to	approx. 7 m significant	4 m significant	2 m significant	0,5 m maximum
Typical Beaufort wind force	up to 10	up to 8	up to 6	up to 4
Calculation wind speed (m/s)	28	21	17	13

MCA (Maritime & Coastguard Agency) rules for sailing vessels.

These rules stipulate an "acceptable" minimum AVS for a range of areas of operation, as shown in Figure 5

They also include a maximum steady heel angle based on a gust wind heeling moment that would heel the boat to 60 degrees, or the downflooding angle if less.

7.2. Variable ballast yachts

Variable ballast yachts have asymmetric stability curves. Figure 1 shows typical GZ curves for a canting keel yacht of modest beam (red curve), and a water ballast yacht (blue curve) together with the GZ curve for a conventional yacht. The interpretation of the behaviour of yachts with asymmetric righting arm curves warrants some explanation.

Canting Keel.

Positive heel angle is heeling with the bulb on the windward side, i.e. the conventional sense. There is a stable equilibrium at –23 degrees (an angle of "list") a positive GZ at zero degrees and a "Capsize Point" at 113 degrees. On reaching the capsize point the heel angle would continue to increase until it reaches the angle of list at –23 degrees, having rotated completely through the mast vertical condition.

Heeling in the negative direction from the angle of list, there is no capsize point, so no matter how far the yacht heels to windward it will never capsize, but always return to the angle of list.

Water Ballast Yacht.

Similar behavior is shown by the water ballast yacht in that it has an angle of list (-11 degrees), positive GZ at zero heel, and a capsize point at 105 degrees. The major difference is that there is also a stable equilibrium condition, with the yacht essentially upside down, at –169 degrees of heel (+191 degrees). This means that on exceeding the capsize angle the yacht will move to the stable equilibrium condition at –169 degrees. Once in this nearly inverted condition the return to the upright condition is easier moving in the positive heel direction, where the maximum opposing GZ is 0.4m. as opposed to the negative direction where the GZ peak is –1.78m.

In general

For all types of boat, if there is a condition of stable equilibrium between "Capsize" points then the yacht is not self righting and may remain in an inverted condition if capsized. Yachts with moveable ballast will have asymmetric GZ curves, and this means that righting from the inverted position is easier in one direction than another. This raises the question as to the extent to which active participation by the crew might be permitted in the assessment of stability characteristics.

7.3. Possible regulatory constraints

How does the tried and tested regulatory regime for "symmetrical" hull forms apply to asymmetric hull forms ? What might be considered unacceptable features of conventional yachts ?
Too low an AVS,
Too low a GZ at 90 degrees of heel such that a gust/broach knockdown results in a capsize.
Too tender to have acceptable gust response.
Too low a downflooding angle.

Notwithstanding the asymmetric nature of the GZ curves, or the mechanical engineering of the canting keel the same unacceptable features should be excluded in moveable ballast yachts.

Current Race Regulations.

IMOCA **Open 60** Rules require:

1. Determination of the position of the centre of gravity of a boat weighed empty and measured at 90 degrees heel.
2 AVS with keel on the centreline and/or ballast tanks empty shall be greater than or equal to 127.5 degrees.
3 The volume of ballast tanks and/or keel cant angle are not limited other than by the rule of a maximum of 10^0 static heel angle each way (i.e. 20^0 maximum from one side to another).
4. An inversion and re-righting test without mast.
5. Positive area under the GZ curve shall be at least 5 times greater than the negative area.
6. No limitation of BMAX, Freeboards, DSPM or Sail Area.
7. Boats must be buoyant.
8. 6 Watertight Compartments are required, i.e. 5 watertight bulkhead + a crash box.
9. Exit hatch must be fitted on the transom.
10. Any gear except batteries can be used as movable ballast.
11. Canting masts are not allowed.

Volvo 70 Rules require:

1. A maximum keel cant angle of 40^0 relative to the hull
2. Minimum AVS with the keel fully canted of 115^0. This will equate to AVS with the keel on the centreline of c135^0 to 140^0.
3. A minimum empty boat weight of 12500 kg and minimum bulb weight of 4000 kg.

The Open 60 and Volvo 70 regulations are simple, and are able to be so **because the other hull dimensions are constrained.**
The 10 degree static heel angle is a measure of available righting moment, it does not provide the basis for assessing the self righting or knockdown resistance capability, it does however restrict the amount of moveable ballast, just as the Volvo Rule does with its displacement limit and maximum cant angle.
The self righting test without mast is relatively easy to comply with, and is as much a demonstration of seaworthiness as a measure of self righting capability when fully rigged. The specification of a minimum capsize angle in the Volvo rule does ensure the degree to which the yacht is self righting, and has sufficient knockdown resistance. Given the dimensional tolerances of the rule and the maximum keel cant angle, the fixing of a single point on the GZ curve defines the character at all other angles

IMS Regulations for 2004.

IMS provides not only a handicapping regime, but also an associated set of safety criteria. Consequently when moveable and variable ballast yachts were included in IMS the safety screens also needed to be developed. The capsize recovery requirement was addressed by adopting the existing stability indices, using the capsize angle for both heel directions. Additional concerns were raised about the magnitude of the righting arm in a situation where a broach (to windward or to leeward) put the mast in the water. There was a desire to ensure that a knockdown did not become a capsize. Also the narrow canting keel boats have relatively low area under their GZ curves up to 90 degrees of heel when the yacht heels to windward.

Knockdown Recovery.

The ISO STIX formulation contains a Knockdown Recovery Factor, (section 6.4.4) and whilst this is only one factor used in determining the STIX formulation, it was considered a viable parameter by which to judge the available righting moment at 90 degrees of heel.
Figure 8 shows the FKR values for the yachts examined in developing the regulations, using the GZ values for both plus and minus 90 degrees of heel.

6.4.4 Knockdown recovery factor (FKR)

This factor represents the ability of a boat to spill water out of the sails and hence recover after being knocked down.

Calculate

$$F_R = (GZ_{90} m / (2 A_S h_{CE})$$

where

m is the mass of the boat in the appropriate loading condition, expressed in kilograms;

GZ_{90} is the righting lever at 90° heel, expressed in metres, for the boat with a mass of m;

h_{CE} is the height of centre of the nominal sail area (A_S) above the waterline, when the boat is upright, expressed in metres, for the boat with a mass of m

Two factors informed the discussion about "acceptable" limits of FKR_{90} and FKR_{-90}, firstly the ISO range of 0.5 to 1.5, and secondly the trends of FKR values from the IMS yachts.

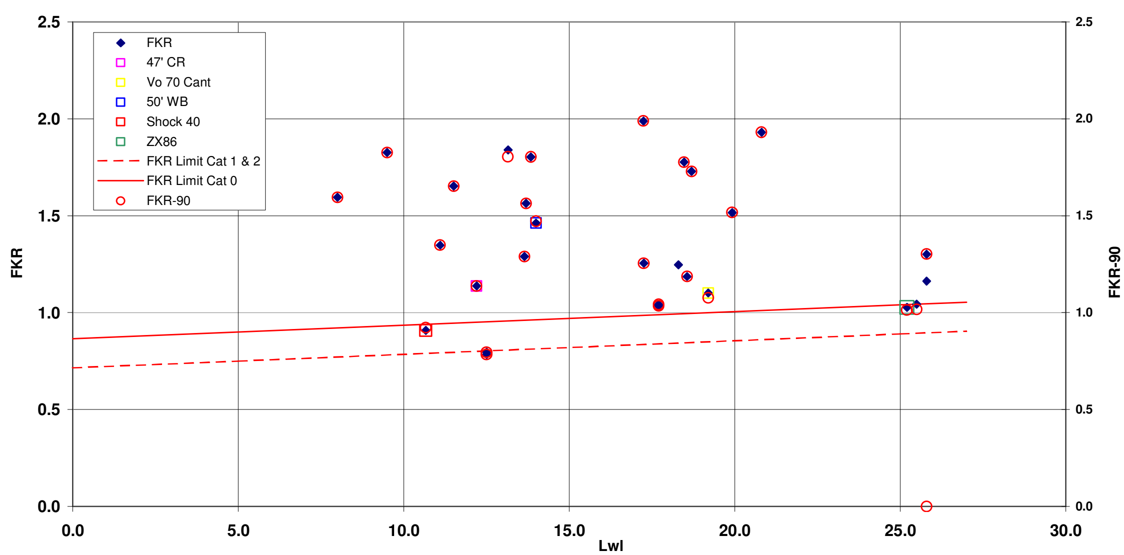


Figure 8. ISO Knockdown recovery factor (FKR) values.

Shown on Figure 8 are the FKR limits proposed in IMS for Category 0 (solid line) and Categories 1 and 2 (dashed line).
This proposed factor was modified to create the IMS Ballast Leeward Recovery Index for 2004.
No formal regulation was framed about area under the righting moment curves up to a heel angle of 90 degrees, but a form of words that alerted inexperienced crews to the unusual nature of the righting moment curves was included in Appendix 10 of the IMS rule. The related extracts from the IMS rule are contained in Appendix 1.

8. References

1) INDUCED DRAG OF MULTIPLANES.
L.Prandtl. NACA TN 182, March 1924
2) THE DYNAMIC STABILITY OF SAILING YACHTS IN LARGE BREAKING WAVES
A.R. Claughton
International Conference on Design Considerations for Small Craft, February 1984
3) FINAL REPORT OF THE DIRECTORS.
Joint Committee on SAFETY FROM CAPSIZING.
USYRU. June 1985
4) REPORT OF THE 1998 SYDNEY HOBART RACE REVIEW COMMITTEE.
May 1999.

Appendix 1.
Extract from IMS Rule

205. Stability.
1. Limit of Positive Stability (LPS): A yacht shall not be issued a valid IMS certificate if her IMS upper Limit of Positive Stability is less than 103.0 degrees.

2. Stability Index: As provided under IMS Regulations 201, a yacht's eligibility for entry in IMS races of Special Regulations Categories 0, 1 or 2 may be limited on the basis of her Stability Index as noted in the "Limits and Regulations" section of her IMS Rating Certificate (see Appendix 1).
Stability Index is calculated as follows.
Stability Index = LPS + Capsize Increment (CI) + Size Increment (SI)

Where, in imperial units:
CI = 18.75*(2.0-MB/(DSPM/64)^.3333)
SI = (((12.0*(DSPM/64)^.3333+LSM0)/3.0)-30.0)/3.0
CI shall not be taken as greater than 5.0 nor less than -5.0.
SI shall not be taken as greater than 10.0.

3. Ballast-Leeward Recovery Index (BLRI): For a yacht incorporating water ballast or a canting keel (see Appx. 10), eligibility for entry in IMS races of Special Regulations Categories 0, 1 or 2 may be limited on the basis of Ballast-Leeward Recovery Index (the value of BLRI on the Rating Certificate) as recommended below.
a) The BLR Index represents such a yacht's relative ability to recover from a knock down with sails aback, i.e., knocked down with all water ballast or canting keel to leeward. BLR Index iscalculated as follows:

BLR Index = (RA90*DSPS/(2*SA*CE))*0.333 + 0.5

Where, in metric units:
RA90 is the righting arm, 90 degrees heel, IMS Sailing Trim.
DSPS is the IMS Displacement in Sailing Trim.
SA is the geometric area of the IMS rated sailplan, i.e., mainsail and foretriangle.
CE is the Center of Effort of the IMS rated sailplan, i.e., mainsail and foretriangle.
(all taken with full leeward cant or leeward ballast tank age full, windward empty)

b) The Limits for minimum BLR Index are specified according to Special Regulations Race Category (0, 1 & 2) and vary with IMS sailing length in Sailing Trim, "LSM1" (see IMS 518).
They are therefore displayed on the Certificate as SRCat0 Minimum and SRCat1&2 Minimum.
The limits are calculated as follows.
SR Category 0: Minimum = 0.90 + 0.007*(LSM1 - 5)
SR Categories 1 & 2: Minimum = 0.75 + 0.007*(LSM1 - 5)

IMS APPENDIX 10 -- WATER BALLAST & SPECIAL APPENDAGES

As agreed at the November 2003 Annual General Meeting of the Congress, the ORC International Technical Committee developed for implementation Spring, 2004, prescriptions and formulae for rating on a rational basis yachts with canting keels, bilge boards and trim tabs, including a full revision of procedures for rating yachts with water ballast in order that event organizers who may wish to include such yachts in IMS racing can do so on an equitable basis.

Stability:

In addition to relevant measurement and rating data, 2004 Rating Certificates for canting keel and water ballasted yachts will display both the familiar Stability Index (see IMS Regulations 201) and also a new Ballast- Leeward Recovery Index (BLRI). The BLR Index is related to a yacht's estimated ability to recover from a knockdown to windward where the moveable ballast is on the leeward side. The 2004 IMS Regulations were printed before the provisions for movable ballast yachts were finalized. In that printing, a higher Stability Index is specified for Water Ballast yachts than for conventional yachts. This no longer applies; the Stability Index recommendation for all movable ballast yachts is the same as that for conventional yachts. Likewise, IMS Regulation 201 does not include the BLR Index recommended limits. These are given in IMS 205.3, General Limits and Exclusions, Stability, herein. The formula for calculation of the BLR Index is given in that section as well.

The stability criteria for moveable ballast yachts (water ballast or canting keel) have been set to achieve similar levels of capsize resistance and recovery as conventional yachts. However the defining feature of moveable ballast yachts is that, with the ballast deployed, they have an angle of list, i.e. a static heel angle that is not upright. Consequently the energy required to heel the yacht to 90 degrees (i.e., spreaders in the water) is generally more when heeling with the ballast to windward (normal sailing) than it is with the ballast to leeward (caught aback). Printed on the certificate of all moveable ballast yachts are three values that define this situation for that specific yacht and provide a means of comparison with conventionally ballasted yachts of similar size.

1) the area under the righting moment curve to 90 degrees of heel with ballast to windward.
2) the area under the righting moment curve to 90 degrees of heel with ballast to leeward.
3) an average area under the righting moment curve of a selection of conventionally ballasted IMS yachts of a similar sailing waterline length (LSM1 on the certificate).

These values are not directly entered into the Stability Index or Ballast-Leeward Recovery Index (BLRI), but do offer an indication of the relative ease with which the vessel may be heeled to 90 degrees, both under normal sailing conditions and when "caught aback". Owners and crew should be aware of the different characteristics of moveable ballast yachts when the ballast is to windward AND to leeward.