TECHNICAL NOTE
for the attention of the
SPECIAL REGULATIONS COMMITTEE

Subject : Submission 27-03 from the RYA « CANTING KEEL »

Jean SANS
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Translate by Simon FORBES (ISAF) and Jean SANS

STABILITY of YACHTS BUILT WITH CANTING KEELS (or WATER BALLAST).

Preamble :
At the end of the 1980s , the canting keel appeared on the IMOCA yachts (Vendee Globe). These devices replaced the water ballast principally because they increased the righting moment without changing the displacement of the yacht.
The technology evolved very quickly, the mechanical systems of swing keels existing now in the catalogues of various manufacturers and for boats 40ft to 150ft. The Mini 6.50 are also equipped with these systems but the control mechanisms are more rudimentary. The Class rules of the first Vendee Globe limited the length overall and maximum heel to 10degrees on each side. The IMOCA Class did not exist at this stage.

The CHS rule then IRC took this 10 degree rule, following the request of many designers this prescription was removed in 2002. At the same time the influence of canting keels and water ballast on the speed of the boat are taken into account in the IRC Rule in order to limit certain architectural excesses. This type of boat is also common on the West Coast of USA.

Today a great number of boats from 6.5m to 42 m are equipped with a canting keel.

The architectural excesses which were committed at the time on the Vendee Globe[1] boats saw drastic measures taken by the organisers FICO and by IMOCA.
These measures have limited the design innovations. Today if the IMOCA yachts are more sure in terms of stability, it is not evident in the case of all the boats constructed for the IRC for example or other measurement systems. A general measurement rule is not in principle the system best adapted to control the stability of the boat (see IOR or IMS), only a box rule is really able to do this effectively. This is noticeably the case in the rules of the Volvo Ocean Race or that of IMOCA.

Before studying the influence of canting keels on the general stability of a yacht we look at how this stability is achieved.

Note also that until 1996, the ORC rules required that boats be « self-righting ». After several catastrophes in the Southern Ocean the stability requirements were written differently by the Special Regulations Committee.

<u>General analysis of static stability</u>

- A « modern » boat with a fixed keel is not self-righting, this means that in the event of a capsize it remains inverted. To re-right it is necessary to heel the inverted boat and attain the angle of vanishing stability (Avs)..

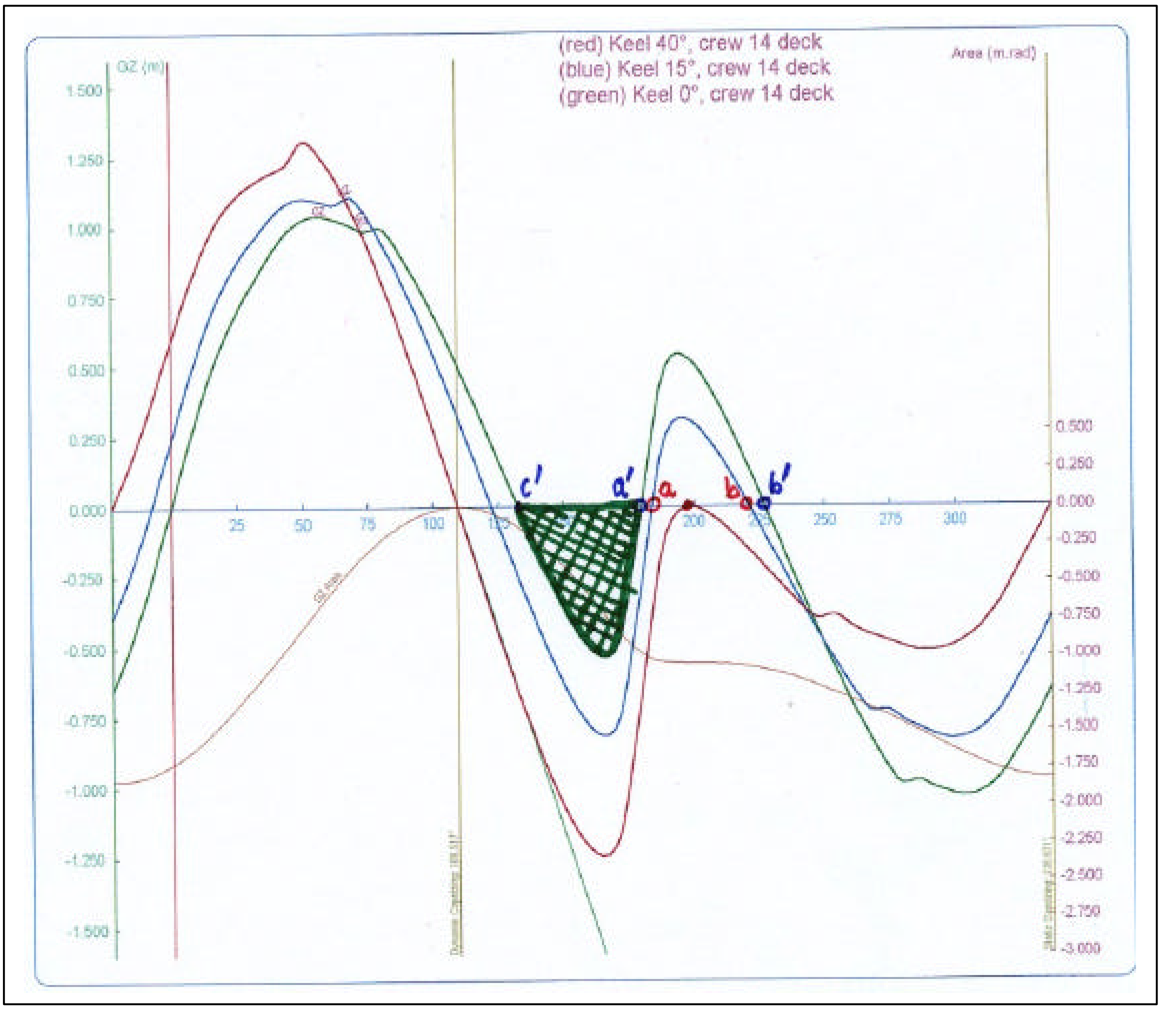
Depending on the type of design of the boat, the angle Avs to be attained after the capsize will be of the order 115° à 170°, that is a heel of 10° à 65°.

In this type of situation (capsize), onlt the energy contained in the waves would provoke this heel angle.

[1] Voir Stabilité des Voiliers 60’ (Jean Sans, traduit par Simon Forbes)

The energy needed to get the boat upright is proportional to the area under the Stability curve and depends on the slope of the tangent of this curve at the 180 degrees point. The more the tangent is vertical the more the boat will be stable upside down and the more energy will be needed to re-right it.

This situation is represented by the curve « green » on the graph below. The difference (a'-c') represents the angle of heel to attain the Avs c' . The hatched area represents the amount of energy that will be needed to obtain this heel angle.



(These three curves are obtained with the crew on the deck , globally centred).

- When the canting keel is inclined to one side (or ballast tanks filled), the equilibrium of the boat is modified, it takes on an angle of heel corresponding to the « upright » position. This heel angle is created by the off-centre placement of the centre of gravity of the boat in general.

If the boat capsizes (360°) in this configuration, the overall stability would perhaps be as follows :

- The curve after the angle of Avs is tangential to the axis of the heel (red curve) or is below this axis. This signifies that the boat is systematically self-righting.

OR

- The curve cuts the axis of heel angle a and b for example, this signifies that the boat remains inverted and that it will need to attain the angle b for it return to upright. One notes that in the case of asymmetry of the centre of gravity of the boat, it is easier to return towards the angle b than to go back towards the angle Avs (d’).

In both these cases the boat capsizes with the keel canted to windward. This configuration of the keel above all increases the initial stability of the boat and its performances. But a boat may capsize in the configuration « keel to leeward[1] », for this it is necessary to read the curve in the other sense.

One notes also :

- Keel to windward : the righting moment is increased in comparison with the with the keel at the 0° position, but the angle of heel corresponding to this righting moment is reduced.
- Keel to leeward : its the opposite

Finally one notes also that a boat equipped with a canting keel is not necessarily self-righting.

Existing regulations

There are two types of existing regulations :

- The regulations instituted by certain class rules, the CCA Rule of 1931 already imposed a measurement of stability and calculated the rating as a function of the stability of the boat.
- The regulations imposed by the government administrations. This type of regulation in different from country to country, above all the European Community put in place since 1998 a unified regulation (STANDARD CE 12217). It is apparent that this regulation goes further than the European continent and almost imposes on the whole world, simply by the fact that the non-European builders have to certify their boats in following this standard, if they wish to have access to the European market.

This CE standard is reserved for pleasure boats and excludes racing boats. In practice, boats entirely destined for racing are extremely rare (60ft ORMA Multihulls, America’s Cup Class). The offshore racing boats are above all cruising boats, even if their comfort is very rudimentary.

Today, there are boats certified to CE and boats (built after 1998 for Europe) certified or homologated by the administrations of the country or even without control. Note that a lower regime exists in the standard CE and that permits state administrations to homologate a boat outside the criteria of the CE standard, and themselves impose a certain number of particular constraints.

The Standard CE 12217

<u>Generalities</u>

The general principle of this standard is to associate the results of a measurement of the stability with the calculated parameters which is used to determine a stability index representing the capacity of the boat to confront the navigation conditions with the most safety possible. This calculated stability index is a number without units called STIX.

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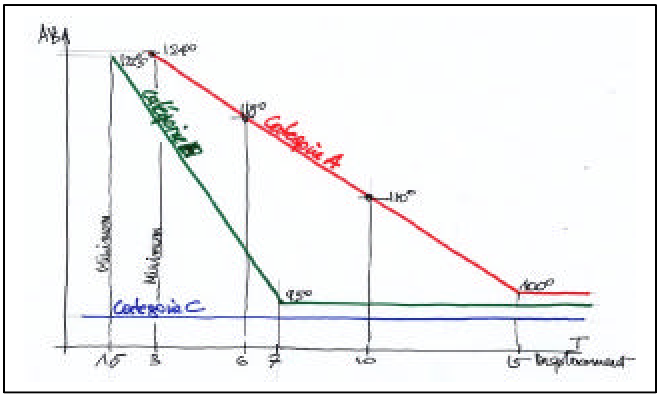
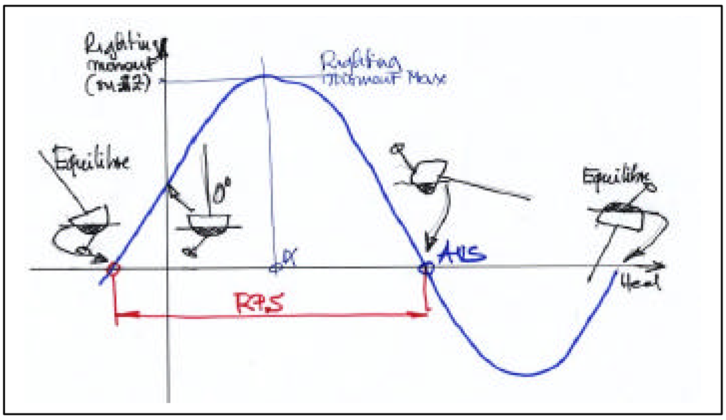
[1] le bateau sous spinnaker par à l’abattée (voir la célèbre photo de BRAVA à l’AC)

La standard CE also defines 4 categories of A, B ,C, D corresponding to the conditions of wind and sea.
Category A (Transatlantic) : STIX >32
Category B (offshore) : STIX>23
Category C (coastal) : STIX>14
Category D (local) : STIX>5

In addition to the requirement on the STIX value, la standard CE 12217 imposes a minimum angle of capsize in category A et B (angle Avs). This Avs minimum is calculated uniquely as a function of the loaded mass of the boat.
Category A : Avs min = (130-0.002* m) and always more than 100°
Category B : Avs min = (130-0.005* m) and always more than 95°
Category C : Avs min = 90°
« m » representing the load mass of the boat (displacement).
One can say that the greater the displacement the more the angle of capsize imposed approaches 100° (category A).



Several standard definitions :
Avs : angle of vanishing stability, it is the angle of heel for which the righting moment is zero.



RPS : Range of positive stability. Used by the Anglo-Saxons, it represents the angular zone during which the righting moment is positive.

In the case of a boat fitted with a fixed keel , the stability curve cuts the intersection of the axes, therefore RPS is equal to Avs.

Limit of the Standard CE 12217

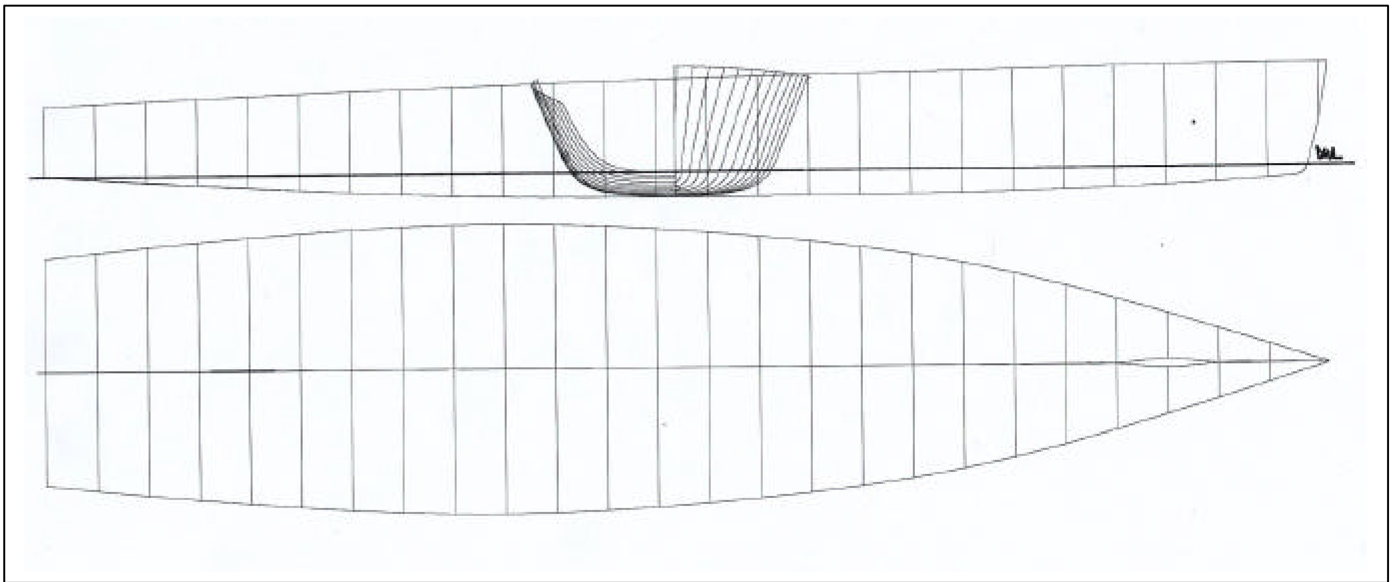
The standard is destined above all for cruising boats, to simplify one could say that it takes into account two types of load to establish the stability calculations (conditions

minimal load et maximum load). It imposes in the case of loading « minimal conditions » a number of passengers » (crew) relatively few (2 for boats of 8 to16 m). These passengers will be placed at the centre of the boat. Evens if the calculations introduce more crew, they are always considered to be on the centreline of the boat.
The standard includes the utilisation of ballast or « asymmetric weight », in the case of the stability the most unfavourable shall be used. The method is identical for the centreboard boats or lifting keels.
This arrangement makes it very difficult for the certification in Category A of yachts equipped with canting keels or centreboards or lifting keels.
The water ballast is less penalised, because the base of the angle of Avs under the effect of ballasts is slightly compensated for by the increase of displacement which generates an increase in the Avs minimum.
The standard does not take into account the effect of crew (crew, packed sails) which is used to laterally ballast the yacht.

COMPARISONS and ANALYSIS
Here we studied two types of boat of around 60’, one very narrow, one very wide.

Influence of the canting keel and of crew on a « narrow » boat.

<u>Model used</u>



LOA 18.50 LWL : 17.73
B max 4.10 BWL : 3.03 m
Draft : 4.10 Bulb 2.8 T Fin Keel 1.0 T
Upwind sail area : 185 m²
Displacement loaded, with a crew of 2 people : 10108 Kg

<u>Evolution of the stability general and of STIX</u>

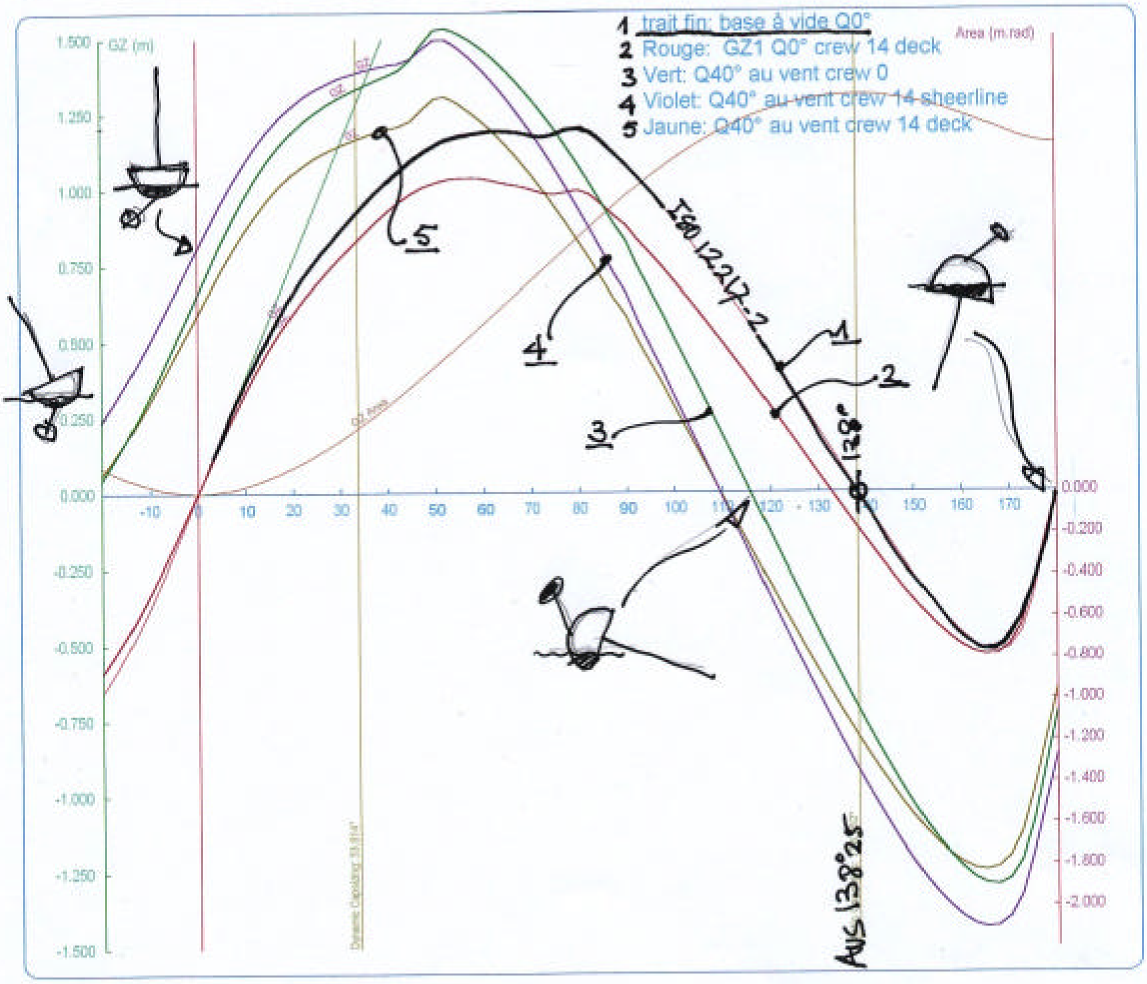
Stability Data, Default criterium, Q 0° hypothese 3, Forms - SISTRE / Sun Oct 12 18 30 23 2003 / page 1/3
Water Density: 1.0250, 2 volumes added (0.379m3 @ x=0.000, y=-3.229, z=8.415)

Chargement mini (voiles, etc, 2 équipiers centrés).

Ship:	10.108t
Sx:	0.000m
Sy:	-0.395m
Sz:	8.415m
Tanks:	0.000t
Tx:	0.000m
Ty:	0.000m
Tz:	0.000m

AP @:	0.000m
FP @:	18.123m
K Point at:	0.000m
KMt:	1.795m
Total Load:	10.108t
TLx:	0.000m
TLy:	-0.395m
TLz:	8.415m

AP Draft:	-0.004m
FP Draft:	-0.001m
Trim:	-0.004m
Heel:	0.000°
GM0:	2.190m
UMt:	0.386t.m



GZ Max @ 79.696° > 25.0°

[0°, 30°] Area = 0.256 > 0.055 m.rad
[0°, 40°] Area = 0.421 > 0.090 m.rad
[30°, 40°] Area = 0.165 > 0.030 m.rad

GM0 = 2.190m > 0.150m
GZ Max = 1.201m ISO 12217-2
GZ 30° = 0.857m > 0.200m

C:\Program Files\dossiers JS 10-2002\ORC 2001\ORC 2003\ETUDE\WOcantingkeel 2.mas / \etude canting keel\(no name) / MAAT-Plus

ISO 12217-2 : 2 crew member on center line (Quille 0°)

Curve 1 *:*
Minimum load (Standard 12217) with 2 crews in the cockpit .
Keel on the centreline
Avs :138°25
RM 1° : 0.386 t.m

Curve 2 :
Take in count 14 crew on the deck and the equipment :
Displacement total : 11228 kg
Keel on the centreline
Avs : 132°
RM1° : 0.380 t.m
Note: the centre of gravity raised, the overall stability diminished.

Curve 3 :
Minimum load (Standard 12217) with 2 crew in the cockpit .
Keel angled at 40°
Avs :115°
This configuration gives the maximum righting moment (Gz=1.533 m) which is 28% more than in the same conditions of load (curve 1) when the keel is on the centreline.

Curve 4 :
Load identical to that of curve 2, but the crew is sitting on the rail.
Keel angled at 40°
Avs : 109°
In comparison with the preceding case, the centre of gravity is raised (crew is on the deck), the maximum righting moment is reduced slightly (Gz=1.496m), -2.5%.
On the other hand the Avs lowers a lot : de 115° à 109°

Curve 5 :
Still with the keel angled at 40°, but the crew is on the deck.
The stability is then very degraded in the level of righting moment.

<u>We can summarise that the angulation of the keel at 40° induces :</u>

- **A significant increase in the righting moment**, when the crew is off watch.

Note that the crew is sitting on the rail but the angulation of the keel is 0°, the following results are obtained :

Avs =127°2 RM1°=0.374 t.m GZ maxi=1.169 m

In the same conditions, note the crew and angulation of the keel to 40°)
(curve 4), the angulation of the keel to 40° generates an increase in GZ of 28%.

- **A significant decrease in the angles of Avs**

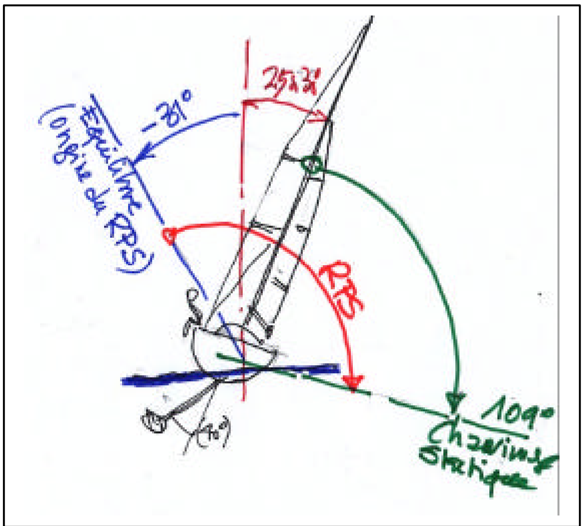
One passes from 138° (keel 0°, 2 crew) à 109° (Keel 40°, 14 crew sitting on the rail) which is 29° less.

If one compares the case of the load corresponding to a boat racing
Keel 0°, 14 crew off watch : Avs = 127.2°
Quille 40°, 14 off watch: Avs = 109° which is 18. 2° less.

STUDY Canting Keel JS - ship narrow -					
	conditions ISO Keel 0°, crewmember: 2	Keel 0°, crewmembers: 14 on centreline (deck)	Keel 40° windward, crewmembers: 14 on sheerline	Keel 40° windward, crewmembers: 14 on centreline	Keel 40° windward, crewmembers: 2 on centreline (ISO)
Mass (displacement) (Kg)	10 108	11 228	11 228	11 228	10 108
Avs (°)	138	132	109	109	115
AVS (°) min STIX	*110*	*108*	*108*	*108*	*110*
Gz 90° (m)	1,083	0,878	0,667	0,753	0,823
positive area under Gz curve (m.rad)	1,917	1,588	2,220	1,828	2,223
RPS	139	132	141	133	137
STIX >32	A - 70,60	A - 65,08	A - 56,57	A - 57,55	A - 59,79

One observes that the RPS is practically unvarying, this is to watch that the parameter badly describes the ability of the boat to resist capsize.

The Avs and the STIX are in my view better adapted. The Avs represents the reel static angle of capsize. Knowing that the boat tries to sail with a maximum heel of 25 to 30° when the wind increases, the skipper adapts the sail area and the righting moment of his boat (by canting the keel to windward) in order to obtain this average angle of heel. The smaller the angle of capsize (Avs) the smaller the difference between the sailing angle of heel (25/30°) and the angle Avs . The range of security is diminished.

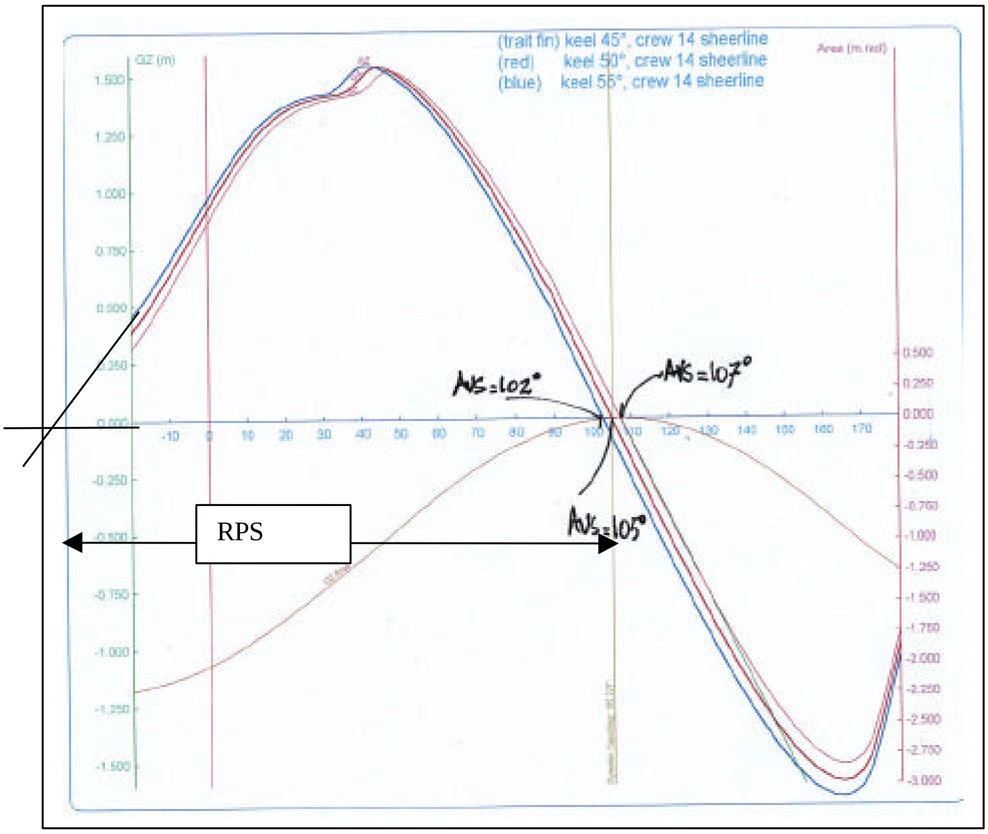


One notes also that the STIX decreases 70.6 à 56.6. and one finds also very close (less than 1°) to the limit the minimum permitted angle Avs (108° for this loaded case). This signifies that the Category A would perhaps be refused for this type of boat.

This model studies is very close to the actual designs (outside IMOCA) that one finds in the IRC races or the Transpac for example.

Influence of the angle of the keel

One could imagine that the designer decides to increase the maximum angle of the keel (we suppose that it is technically possible)
We have taken the same model of crew sitting on the rail.
We have simulated the angle of 45°, 50°, 55°.



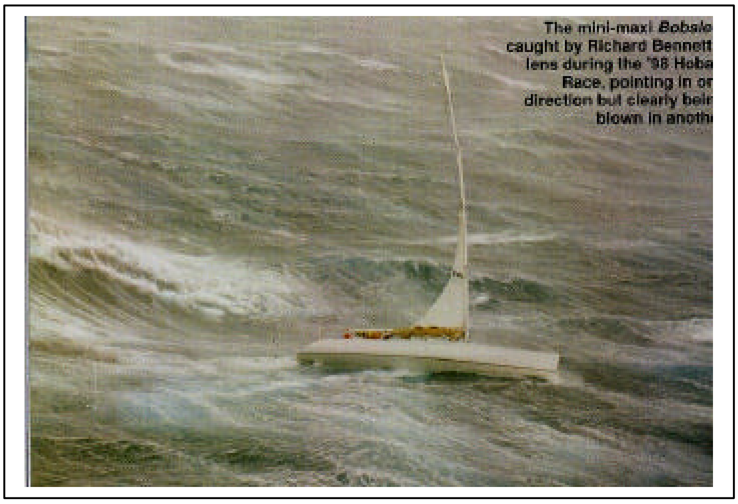
The gain in initial stability at 15° of heel is approximately 9% between the keel angled at 40° et 55°.
But in the 3 cases the Category A would be refused because the angle AVS is less than the minimum required (108°).
It should be noted that in the three cases the RPS is always approximately equal to 140°.

The canting keel increases the power available to the boat and reduces the angle of capsize, its the evolution of this latter parameter that is perhaps the most dangerous.

All of this makes the general stability more like a multihulls, the skipper should not abuse the feeling of power and the very large stability at normal heel angles.

In very bad weather, the temptation to use the canting keel is perhaps debatable.

Some boats better resist the forces which could make them capsize, but the angle of capsize is more easily attained, above all in this situation, the slope and energy of the waves can intervene unfavourably.
The only favourable point in this situation is that the underwater lateral plane is very reduced (one supposes that the daggerboards are lifted) : this in turn reduces the lateral resistance offered by the hull allowing it to slide sideways when otherwise it may be rolled by the beam-on impact of a breaking wave .



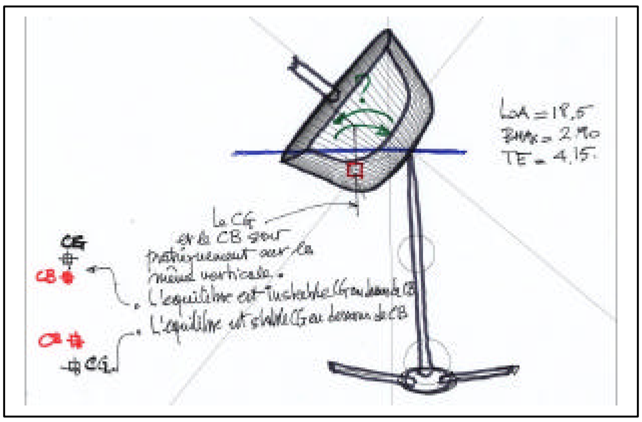
What will be the reaction of this boat with a keel angled at 40° ?

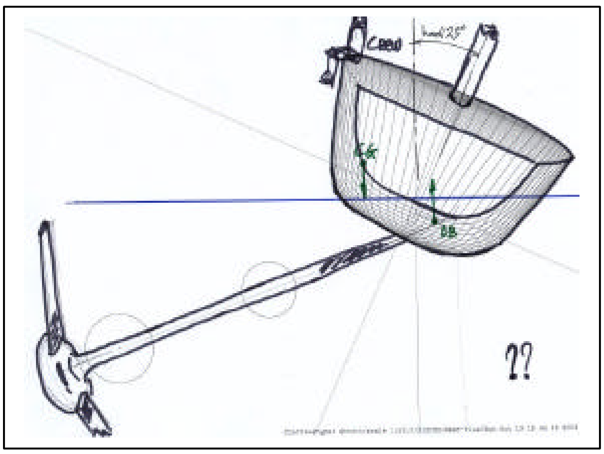
The study above is a study of the static stability. The dynamic stability est for sure much less, notably the angle Avs diminishes normally dynamically. The static stability gives nevertheless an excellent appreciation of the ability of a boat to resist a capsize, et represent a good basis for reflexion for the Special Regulations Committee

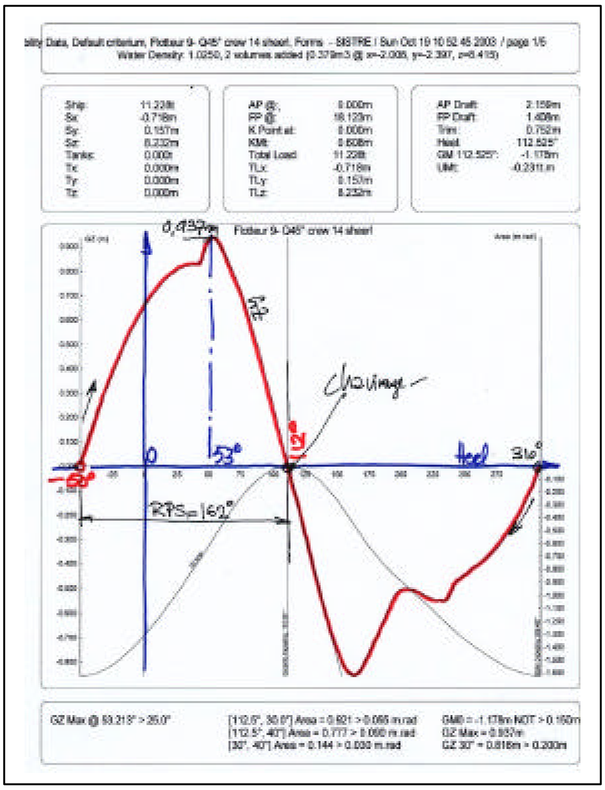
<u>What research for the designers with canting keels ?</u>

The interest in the canting keel is to adjust the righting moment in accordance with the need (about 30% or more of the righting moment than when the keel is on the centreline). The canting keel permits the designer of a narrower boat to reduce the wetted surface and the beam area immersed. The form stability is no longer necessary. Certainly the crew sit on the rail is less efficient , but it will act just like a complement.
At the limit, the designers would design hulls close to that of the centre hulls of trimarans and obtain the necessary stability with the canting keel and the hydrodynamic forces with daggerboards (or wings ??) with asymmetric profiles..

<u>Just how far can we imagine ?</u>

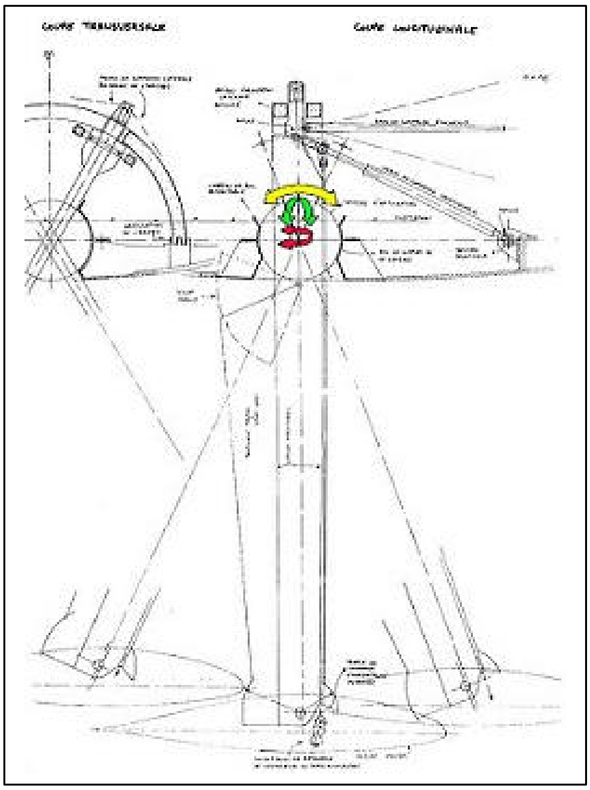


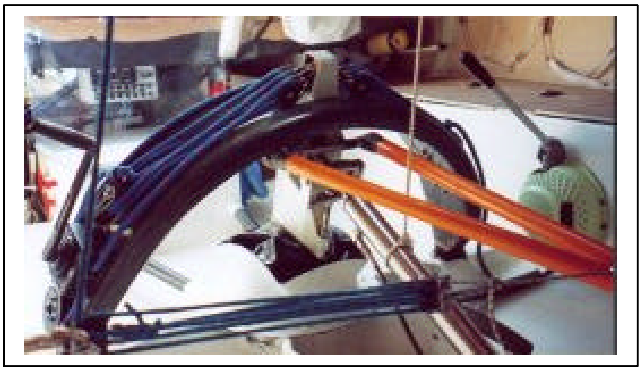




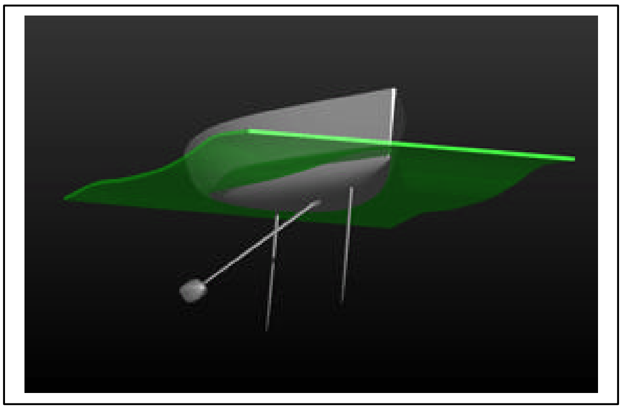
It is possible to imagine a project without taking into account the it stability in terms of performance.
It is evident that faced with these projects, the Standard CE 12217 is very disorientated.

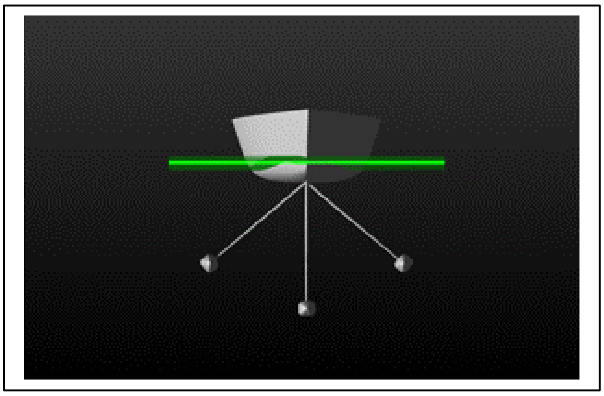
If one consults the Internet one can see that the imagination is a reality in the world of canting keels. Attached are several extracts





System patented   without using hydraulics (3 rotations possible)

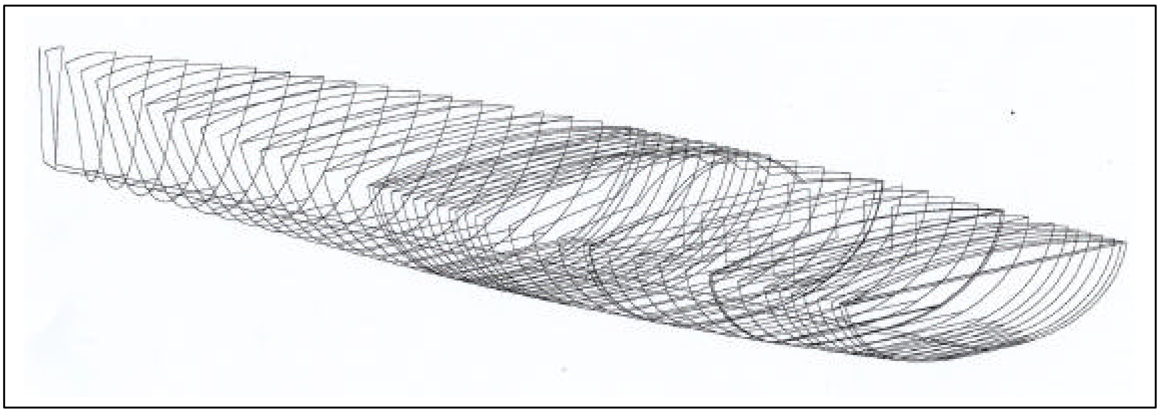




Installation of a canting keel on an old boat (modification).

Influence of a canting keel on a « wide » boat

<u>Model</u>



Design type IMOCA

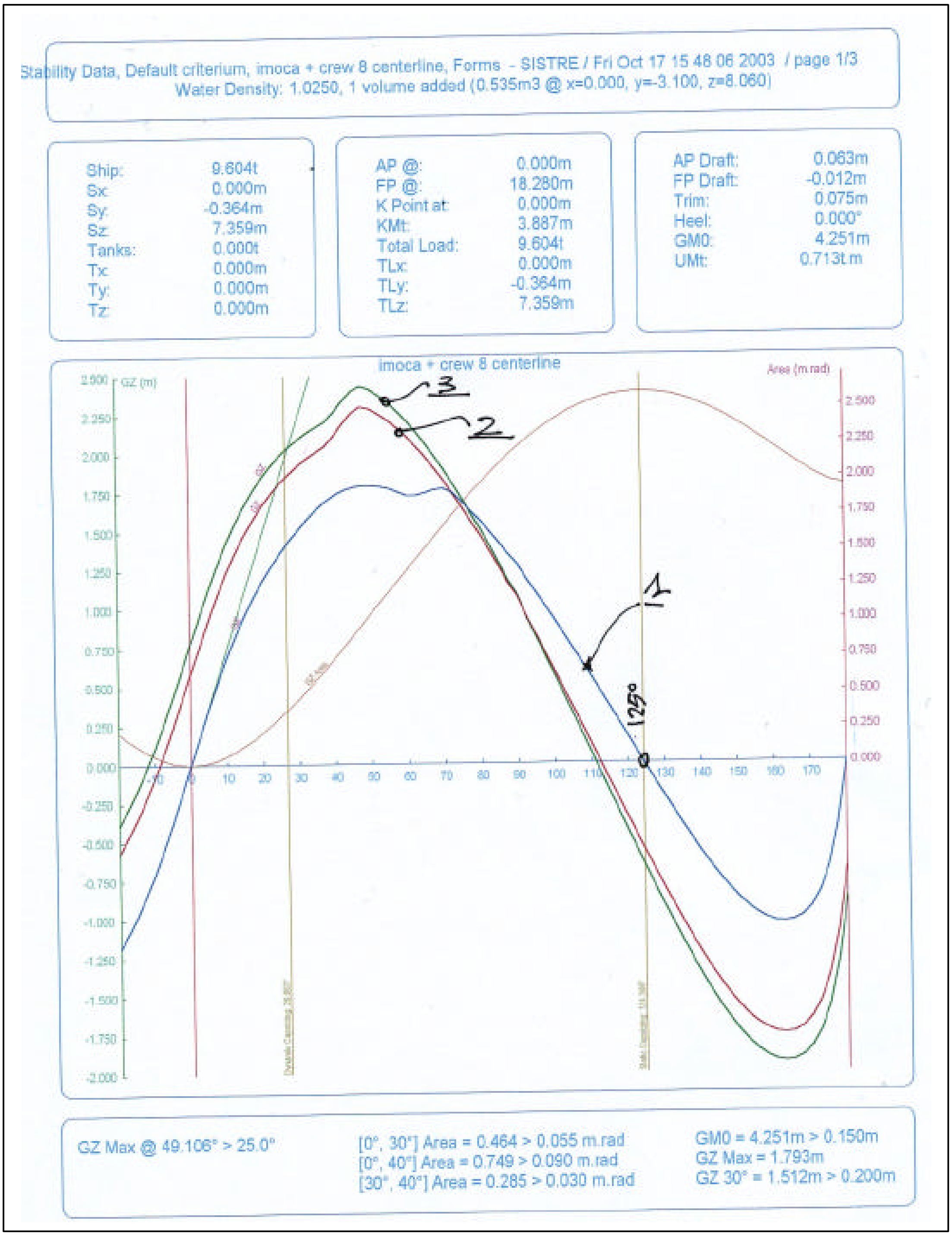
LOA 18.288	BMAX= 5.77	BWL : 3.72 m
TE : 4.50	Bulbe 3.2 T	Voile de quille 1.0 T

Surface de voile au près : 250 m²

Displacement loaded, with a crew of 8 persons : 9600 Kg

The IMOCA box-rule generates a style of boat very wide, because it imposes (see preamble)

that the heel angle does not exceed 10° (without crew, no sails in position) when the keel is canted completely to one side or when the ballasts on one side are full.
This rule imposes the design of wide boats in order to have a form stability which limits the angle of heel when the keel is canted.
<u>Evolution of the stability following the configurations</u>



Curve 1:
The angle of Avs corresponds to a load of 8 crew, boat ready to race. The rule IMOCA imposes an angle Avs of 127.5° boat empty, without sails, nor crew.

Curve 2 :
The keel is angled to 35°, the crew is on the deck at the centre.
the increase of righting moment is significant (28%)

Curve 3 :
The angle of the keel is always 35°, but the crew is sitting on the rail.
For this IMOCA boat, we limited the number of crew members with 8, because accommodations of IMOCA boat are initially designed for the single handles races.

The increase of the righting moment is about 40%.
But in these the last two cases the Avs angle obtained is of 112° and 111°.

The angle limits minimum being for this case of loading (standard EC category A)is:110°7.
These boats are very close to the limit minimum imposed by Standard EC (Avs angle category A).

Paradoxically the boats belonging to class IMOCA, although definite like " OPEN " sailing ships, are much wiser in term of evolution. It is a consequence of the rule of the 10°.
The designer has little freedom, one notes that the only evolutions relates to the appendices, the materials, but that overall the hulls all are rather close.

Conclusions
The evolution of the design of the canting keels throughout the years is very complex, from which we may draw a number of facts and ideas:

Drawings

- The rule limiting the heel (boat " upright") under the effect of the canting keel (or the ballasts) makes it possible a priori to limit architectural excesses.
- But it will lead towards a standardisation of the designs and will limit the innovations.
- The introduction of this rule supposes that ALL the boats are measured.
- The ballasts result in boats not so extreme because their volume is limited by the hull. The use of ballasts is only interesting if the boat have an large Beam.

Construction

- these boats have a more significant risk of to capsize, the keel being entirely rocked specially when material (sails etc.) and crew are on rail.
- But they all are generally self righting, especially if ratio LOA/BMAX is large.
- Once the risk to capsize considered, the risk to consider to see crew-members falling overboard (MOB) become significant. We also have to admit once the boat return upright, she is no more able to sail.

There is a good chance some of these damages may have occured :

- Lost her mast
- damaged sails
- inoperative engine
- water in the boat
- Etc..

Partitioning might be mandatory (watertight bulkheads) in the hull in order to ensure self buoyancy in the event of capsize.

Maintenance

The mechanisms used in the canting keel are relatively sophisticated.

- The force on the top part of the canting keel is significant, because the arm of lever where the hydraulic mechanics cylinder act is weak.

(Ratio - Arm of lever / length of the canting keel : 0.07 à 0.1)

- The structural forces of the boat become very significant because there are all concentrated on weak surface in the vicinity of the axis of rotation of the canting keel.
- the mechanical parts, the hydraulic and electric equipment work in a corrosive and wet environment
- In the event of shock or of contact with an immersed element (floating Object etc.) the disorders with the mechanisms of the keel and/or the structure can be very significant.
- " a small " touch with a fixed keel is not serious, but with a canting keel the consequences (not obligatorily immediate) can be serious.
- Contrary to the boats equipped with fixed keel, <u>a plan of maintenance</u> of the systems mechanical, hydraulic, electric and structure of the boat near the keel must be implemented.
- All the incidents must be obligatorily written in the log book. If this plan of maintenance is not set up and not realised, the risks of accidents are significant.
- a safety mechanical system must be able to make it possible to secure the keel in a position close to the vertical in the event of rupture of the system of operation of the keel.

This technology (canting keel) imposes to the owners and to the crews to permanently check the condition of the mechanisms and the peripherals. It appears obvious to me that a generalisation of this technology will pose problems because it is very complicated to imagine the ageing of this equipment. We have to keep an eye to be on this problem.

Jean SANS
25 October 2003