STABILITY OF MULTIHULLS

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(Translation of a paper dated 10/05/2006 by Simon Forbes)

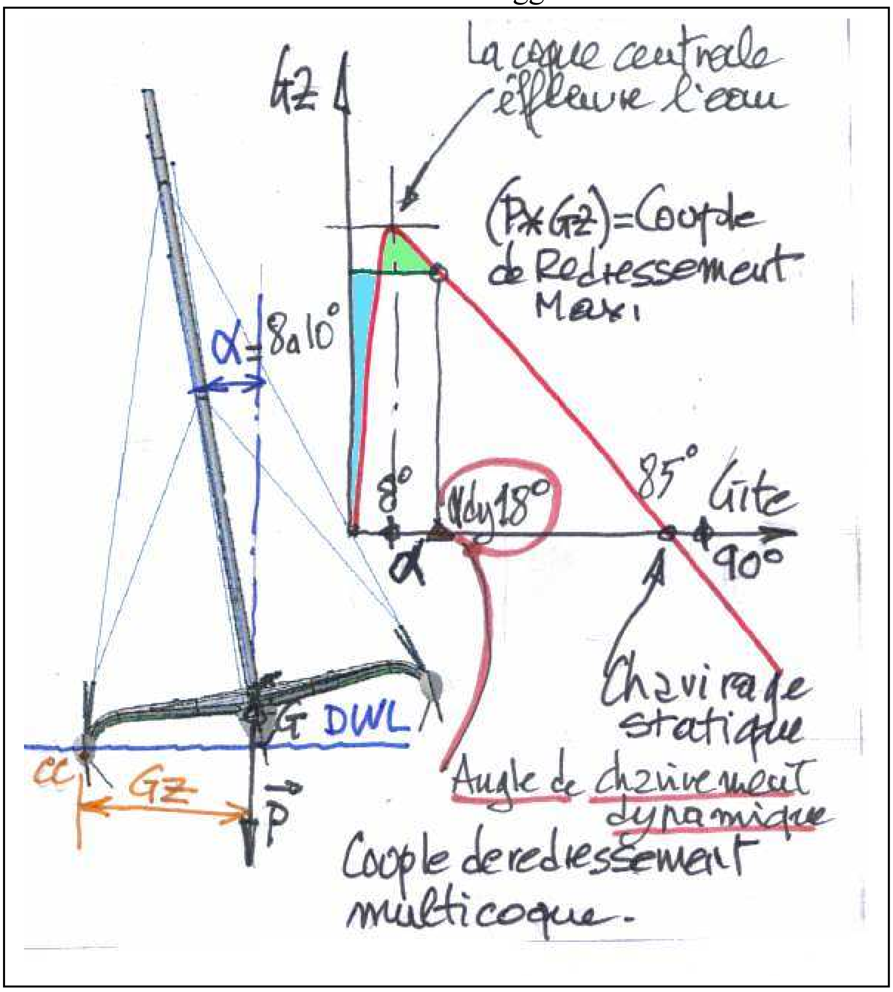
Introduction:

The capsize of Multihulls requires a more exhaustive analysis than monohulls, even those equipped with canting keels. For the latter, the studies of static capsize is sufficient to determine the minimum stability criteria, in order for them to resist capsize and if the boat has capsized, to recover to the upright[1] position.
In the case of Multihulls, it is necessary to study two positions of equilibrium:

(1) Normal position (upright).
(2) Capsize position at 180º.

The special feature in an oceanic multihull is that it can go from position 1 to position 2 (capsize), but never from position 2 to position 1.
An oceanic multihull is also characterized by a maximum righting moment which will be explained in more detail further on: the couple resisting capsize, from 8º to 15º of heeling, depends whether it is a catamaran or a trimaran. The angle of heel corresponding to the maximum righting moment can be obtained as follows:

- For a catamaran, when the windward hull is completely out of water, all the immersed volume is in the leeward hull.
- In a trimaran, when the main hull is completely out of the water (just above the water), all the volume immersed is in the leeward outrigger.



Capsizing of a multihull can occur due to two general situations:
1st Hypothesis: capsize approximately lateral due to an extremely violent wind (>60kn), no sail hoisted, with the speed approximately zero. Capsize of the multihull will be due to the effect of the wind on the mast and the hull.
2nd Hypothesis: Capsize sailing at high speed. In this case capsize is due to dynamic effects.

Study of lateral capsizes (violent wind, boat without sail): Hypothesis Nº1 as above.
In this configuration, we neglect dynamic forces (i.e. boat acceleration), and only static forces are considered. The skipper can only hope that his boat is not overturned like a pancake by the wind.

Analysis of the forces and couples created:

- Couple resisting capsize, which is the one that keeps the multihull upright on the water.

The physical meaning of this "couple" is
(Weight of the boat x horizontal distance measured from its centre of gravity to the centre of buoyancy of the leeward hull or outrigger).

- The couple able to capsize the boat we will call the aerodynamic couple (aero couple). It is created by:
  - Aero couple generated by the effect of the mast perpendicular to the wind.
  - Aero couple generated by the pressure of the wind on the hull side exposed to the wind.

The physical expressions for these two aero couples are:
Mast aero couple:
Aerodynamic force created by the mast x vertical distance between the point of application of this force (approximately mid-height of the mast) and the centre of lateral resistance to leeward.

Hull aero couple:
Aerodynamic force created by the part of the hull exposed to the wind x vertical distance between its centre of pressure (approximately mid-height of the hull side) and the centre of lateral resistance to leeward.

Conditions for the calculations of the aero couples mentioned above (wind basis):
Category of navigation 0 OSR Wind speed 85kn (43.7m/s).
Category of navigation 1 OSR Wind speed 70kn (36.0m/s).

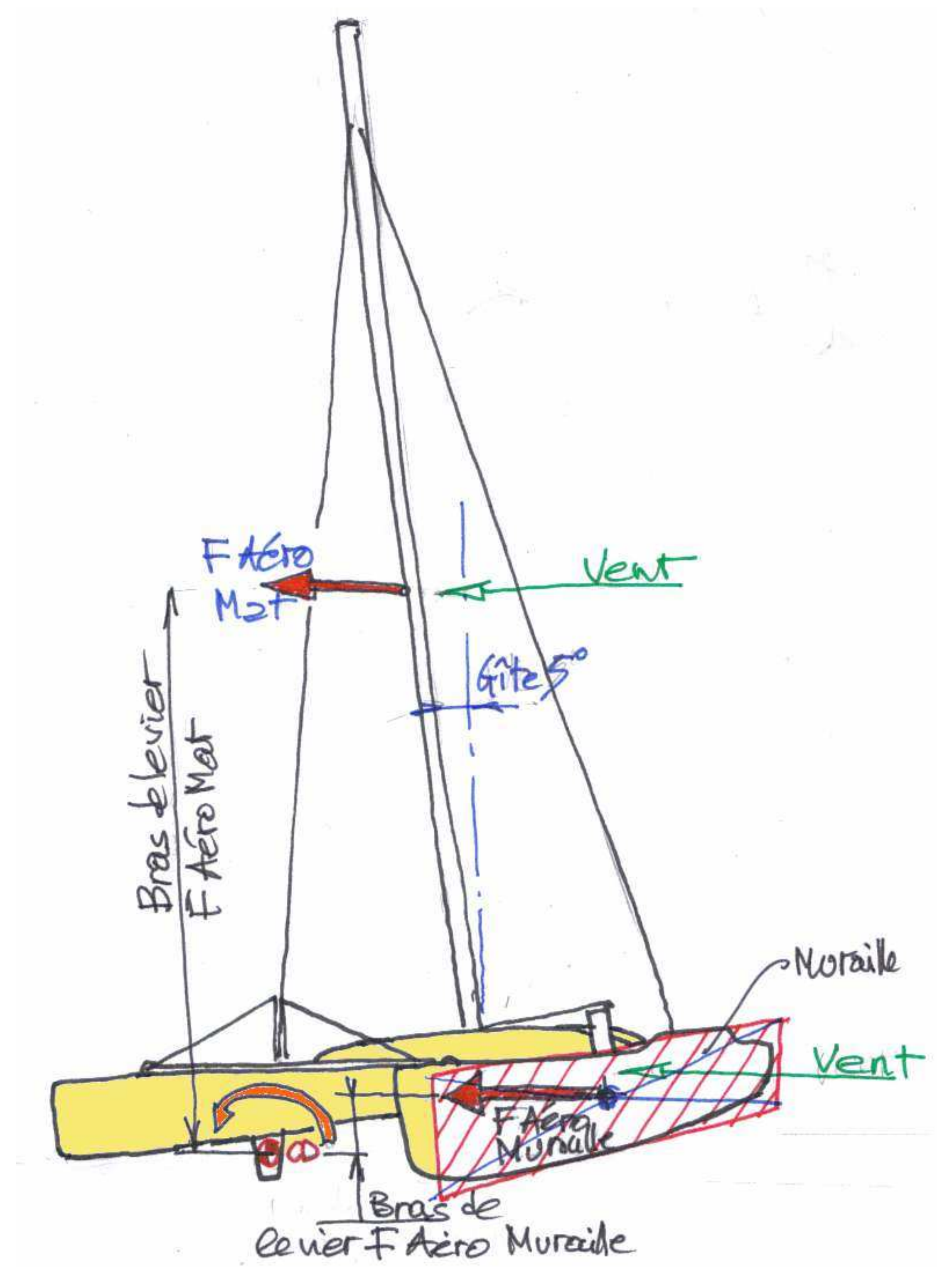
Hypothesis Nº1 : The multihull is leaning on the leeward outrigger or hull and the surface of the water is considered reasonably horizontal.
The heel angle is relatively small, in the order of 5º for a catamaran and 8º to 10º for a trimaran.

(1) CATAMARAN (example ORANGE II)

Principal Characteristics:

LOA	: 36.8m
Beam	: 18m (16.5 between axes).
Total Height	: 48m
Mast height	: 45m
Mast Chord	: 1.05m

Base Displacement	: 28,000kg
Average freeboard	: 2.68m
Centre of lateral resistance	: 1.25m below DWL (Dagger boards up).



Couple resisting capsize (boat mass x distance between axes/2)
Say 28000 x 9.81 x 16.5/2 = 2266110 Nm = 226611 DNxm.

Aerodynamic force created by the mast:
The aerodynamic force created by the mast (cat 0) expressed in Newton is as follows:

$$0.5 \times \text{air density} \times C_x \times S \times V^2$$

Where:
Air density: 1.225kg/m^3
C_x : 1.24 Hydrodynamic coefficient of a flat plate perpendicular to a fluid.
S : Lateral surface of the mast perpendicular to the wind in m^2.
V : Wind speed in m/s.

Say:
Mast aero resistance :(cat 0) = 0.5 x 1.225 x 1.24 x (45 x 1.05) x 43.7^2 = 6853 DN.
Hull aero resistance :(cat 0) = 0.5 x 1.225 x 1.24 x (36.8 x 2.68) x 43.7^2 = 14304 DN.

Aero couples induced by these two forces:

1. In the mast (cat0):

Vertical distance = (Mast height/2) + (height of the mast foot) + (centre of lateral resistance) = 45/2 + 4 + 1.25 = 27.75m.
Note: All distances taken with respect of the waterline except for the mast height.
Couple induced by the mast (cat0) = 6853 x 27.75 = **190170 DNxm**.

2. In the hull (cat0):

Vertical distance = (freeboard/2) + (centre of lateral resistance)
Vertical distance = 2.68/2 + 1.25 = 2.59m.
Note: All distances taken with respect of the waterline.
Couple induced by the hull (cat0): 14304 x 2.59 = **37047 DNxm.**

Hence the resultant of the two forces provoking capsizes are:
Resultant = 190170 + 37047 = 227218 DNxm.

Ratio of the Couple resisting capsize / couple provoking capsize (aero couple):
R = 226611 / 227218 = 0.997
Note that in this hypothesis, the ratio is nearly 1, meaning that the situation in a catamaran is on the limit. Nevertheless, if the expression of the force aero on the mast can be considered close to reality, those of the force aero on the hull is probably overvalued due to effects created by the water surface. These effects are of two types:
The wind shear gradient and the creation of turbulence in the netting. These two effects combined reduce the wind speed. Applying a coefficient of 0.75 to the nominal wind speed, we can obtain the wind speed on the hull:

Nominal wind speed on the hull = Nominal wind speed x 0.75
Nominal wind speed on the hull = 43.7 x 0.75 = 32.77m/s

Under these conditions, force aero on the hull (cat0) becomes = 8043DN
Couple aero on the hull (cat0) = 8043 x 2.59 = 20833 DNxm.

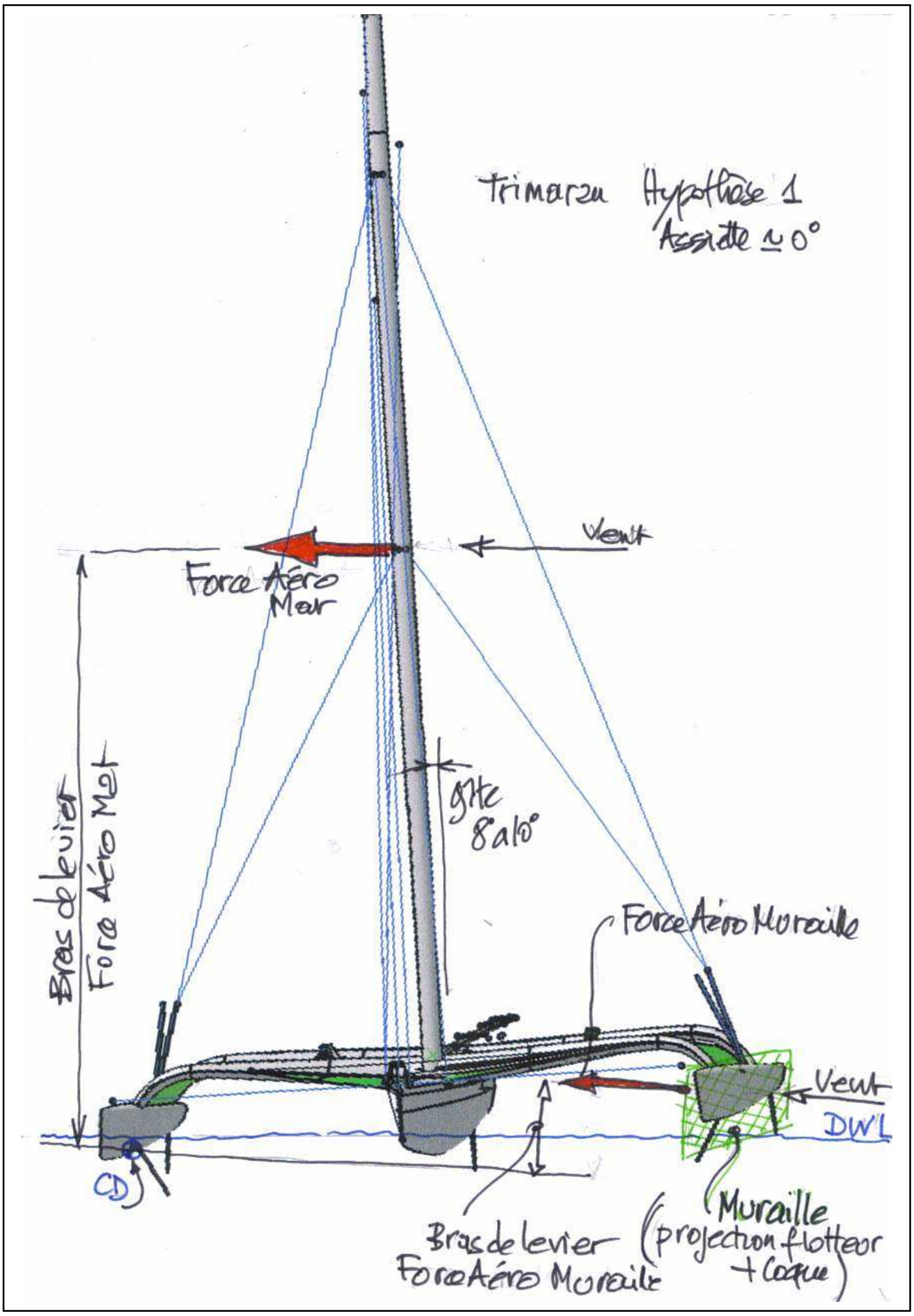
This gives us a **ratio of 1.07** and therefore a safety margin of 7%.

(2) <u>TRIMARAN (example 60'ORMA)</u>

Principal Characteristics:

LOA	: 18.28m.
Max Beam Authorized	: 18.7m (between axes 17.8m).
Centre of lateral resistance (leeward outrigger foil raised)	: 0.25 beneath DWL.
Total height	: 30.48m.
Mast height	: 28.50m.
Maximum mast chord	: 0.85m.
Base displacement	: 5,800 kg.
Mean freeboard with the leeward outrigger supporting 25% of the total displacement	: 2.40m.

The wind speed to take into account is 70kn, which correspond to very bad meteorological conditions such as in the North Atlantic in winter.



Couple resisting capsize = Weight of the multihull x max beam between axes/2
Say 5800 x 9.81 x 17.8/2 = 506392 Nm = 50639 DNxm
Aero force created by the mast (cat1):
Say 0.5 x 1.225 x 1.24 x (28.5 x 0.85) x 36^2 = 2384 DN.

Aero force created by the hull (cat1):
Say 0.5 x 1.225 x 1.24 x (18.28 x 2.4) x 36^2 = 4318DN.

Aero couple induced by these two forces:

(1). In the mast (cat1)

Vertical distance = (mast height/2) + (foot mast height) + (centre of lateral resistance) = (28.5/2) + 1.98 + 0.25 = 16.48m
Note: All distances taken with respect of the waterline except for the mast height.

Aero couple induced by the mast (cat0) = 2384 x 16.48 = **39288 DNxm**

(2). In the hull (cat1)

Vertical distance = (Freeboard/2) + (Centre of lateral resistance)
Vertical distance = (2.40/2) + 0.25 = 1.45m
Note: All distances taken with respect of the waterline.

Aero couple induced by the hull (cat0) = 4318 x 1.45 = **6261 DNxm**.

Hence the resultant of the two forces provoking capsizes is:
Resultant = 39288 + 6261 = 45549 DNxm

Ratio of couple resisting capsize / couple provoking capsize (aero couple) =
R = 50639/45549 = 1.112
The trimaran in this case has a safety margin of 11%

Comment: An increase of 800kg in the total mass of the trimaran (water ballast is compulsory since 2006 for solo racing), changes the couple resisting capsize to: (5800 + 800) x 9.81 x (17.8/2) = 576239 Nm = 57623 DNxm.
Therefore the ratio increases from 1.112 to 1.26 and hence the safety margin increases from 11% to 26%.

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Variation in Hypothesis N^{0}1

The multihull is heeling over the leeward outrigger or hull but it finds itself on a wave which gives it an inclination of approximately 20º.

- CATAMARAN

Couple resisting capsize = Weight of the multihull x GZ
Where GZ = Max beam between axes x cos20º
Say 28000 x 9.81 x 16.5/2 x cos20º = 2129440 Nm = 212944 DNxm

Mast aero resistance (cat0): 0.5 x 1.225 x 1.24 x (45 x 1.05 x cos20º) x 43.7^2
Mast aero resistance (cat0) = 6439 DN

Hull aero resistance (cat0): 0.5 x 1.225 x 1.24 x (36.8 x 2.68 x cos20º) x 43.7^2
Hull aero resistance (cat0) = 13441 DN

Wind couples induced by these two forces:

(1). In the Mast (cat0).

Vertical distance = ((Mast height/2) + (mast foot height) + (depth of the centre of lateral resistance)) x (1/cos20º) = 29.53m

Note: All distances taken with respect of the waterline except for the mast height

Aero couple induced by the mast (cat0) = 6439 x 29.53 = 190143 DNxm

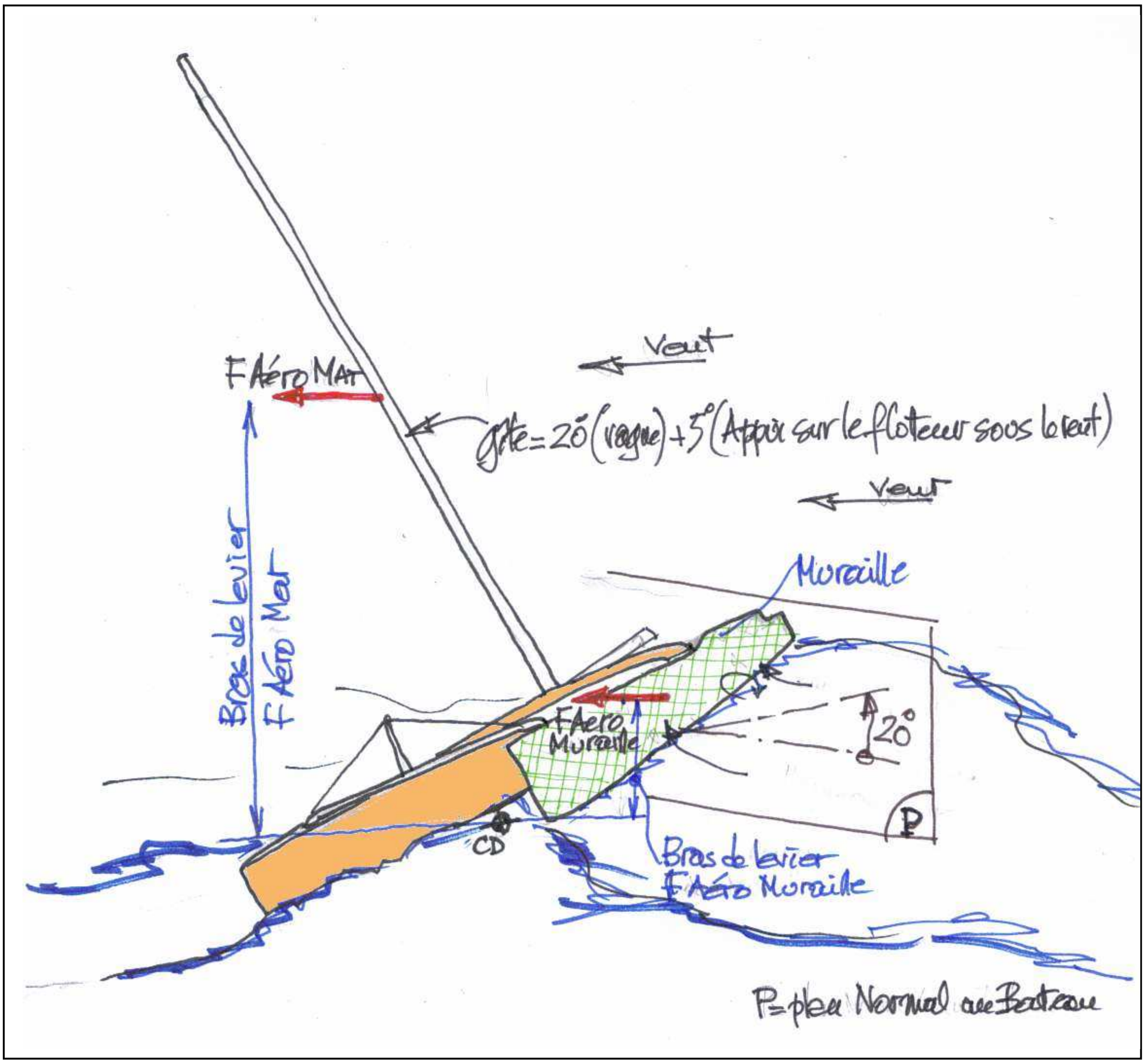
(2). In the hull (cat0).

Vertical distance = ((Freeboard/2) + (depth of the centre of lateral resistance)) x cos20º

Vertical distance = (2.68/2 + 1.25) x cos20º = 2.43m

Note: All distances taken with respect of the waterline.

Aero couple induced by the hull (cat0) = 13441 x 2.43 = 32661 DNxm



Hence the resultant of the two forces provoking capsizes is:

Resultant = 190143 + 32661 = 222805 DNxm

Ratio of couple resisting capsize / couple provoking capsize (aero couple):

R = 212944 / 222805 = 0.956

- TRIMARAN

Couple resistant to capsize:

Weight of multihull x Max Beam between axes/2 x cos20º

Say 5800 x 9.81 x 17.8/2 x cos20º = 475852 Nm = 47585 DNxm

Mast windage(cat1) = 0.5 x 1.225 x 1.24 x (28.5 x 0.85 x cos20º) x 36^2

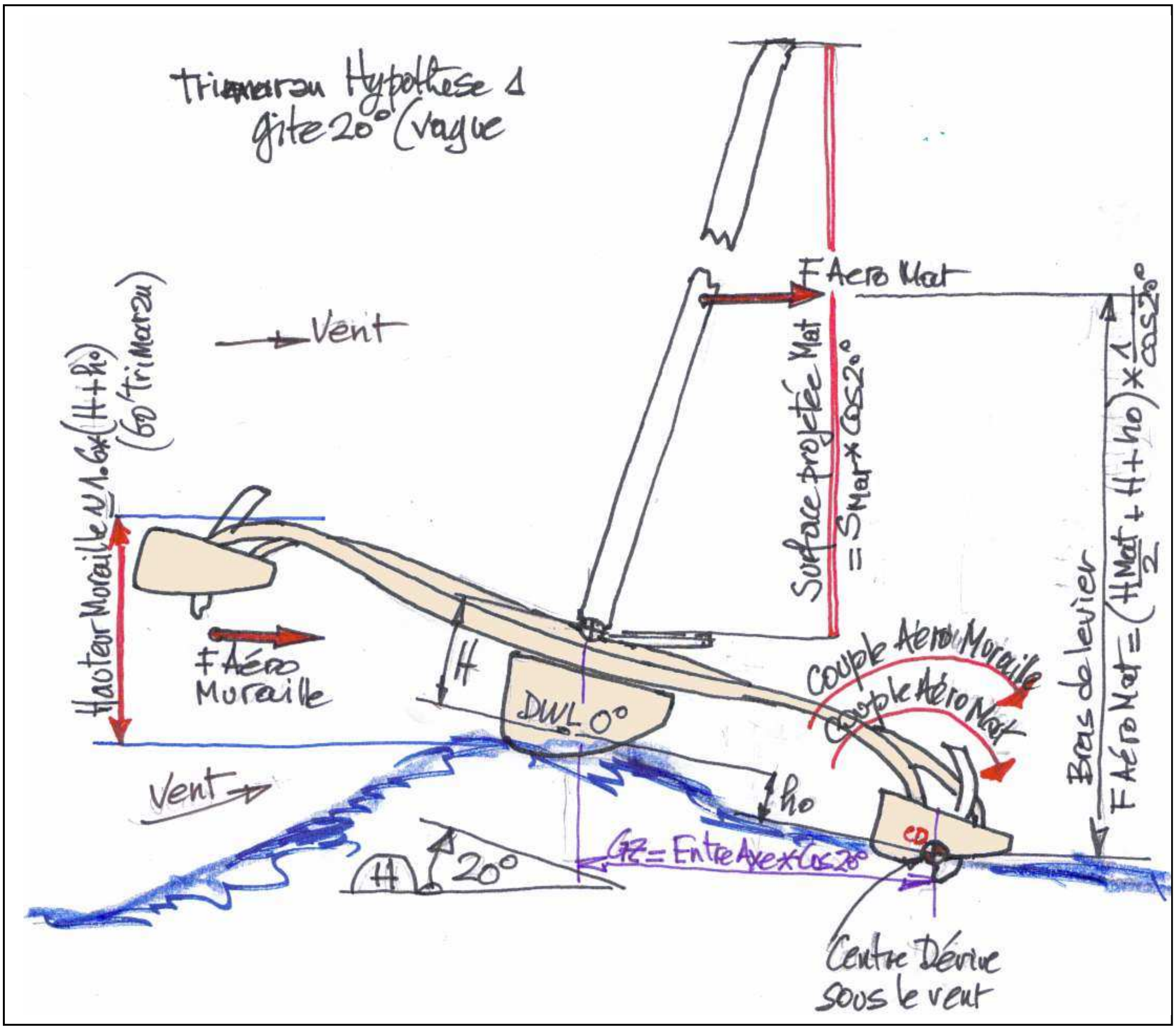
Mast windage(cat1) = 2384 DN

Hull windage(cat 1) = 0.5 x 1.225 x 1.24 x (18.28 x $(H+h_o)$ x 1.6) x 36^2

Where the term $(H+h_o)$ is the height of the main deck above DWL.

Say $H+h_0$ = 2+0.25 = 2.25m *(average value for a 60').*

Hence, Hull aero resistance (cat 1) = 64775 N = 6477 DN.



Aero couples induced by these two forces:

(1). In the Mast (cat1)

Vertical distance = ((Mast height/2) + (Foot mast height) + (depth of lateral resistance)) x (1/cos20º) = ((28.5/2) + (1.98) + (0.25)) x (1/cos20º) = 17.53m

Note: All distances taken with respect of the waterline except for the mast height

Aero couple induced by the mast (cat1) = 2384 x 17.53 = 41809 DNxm.

(2). <u>In the hull (cat1)</u>
Approx vertical distance = ((Max beam between axes/2) x sin20º - h_0) + (Freeboard/2) = 3.9m (see picture above).
Wind couple induced by the hull (cat1) = 6477 x 3.9 = 25383 DN_xm.

Hence the resultant of the two forces provoking capsizes is:
Resultant = 41809 + 25383 = 67192 DN_xm
Ratio couple resisting capsize / couple provoking capsize (aero couple):
<u>R = 47585 / 67192 = 0.708</u>

As the configuration of a trimaran is very different to a catamaran (i.e. the platform of a trimaran may find itself entirely off-balance on a wave), this creates a situation that increases the surface of the hull exposed to the wind.
This implies a ratio (Couple resisting capsize / couple provoking capsize(aero couple)), much smaller (0.708) than that of the boat in the approximately horizontal condition (1.12).The situation of the trimaran is relatively more hazardous compared with the catamaran, which in the two configuration has a ratio close to 1 (0.997 and 0.956).

These calculations are made considering a regular and constant wind flow, and it does not include the effect of friction and turbulences near the surface of the water. These effects reduce considerably the efficiency of the wind pressure over the hull. The couple created by the wind pressure on the hull is then less important than it has been described above. On the other hand, the effect created by the netting when the boat is heeled 20º, is not taken into account and is difficult to measure. In consequence we can consider that the error made ignoring the effect of friction and turbulences for the wind speed can be compensate for not taking into account the effect of the wind pressure against the netting.

Study of dynamic capsize (multihull sailing off the wind at high speed)

- <u>TRIMARAN</u>

This calculations take into account parameters such as the energy accumulated by the multihull (mass, acceleration), and the situation in which the multihull is blocked by a train of waves mainly by the leeward outrigger (stalling of the foil).
The boat is subjected to a strong deceleration (its speed can go from 30kn to 8kn in a matter of seconds), it passes from a longitudinal trim which is almost horizontal, balanced on the leeward foil to a very negative trim (the leeward outrigger dives under and to a lesser extent the main hull).

The axis of rotation is oblique, it can be located enters

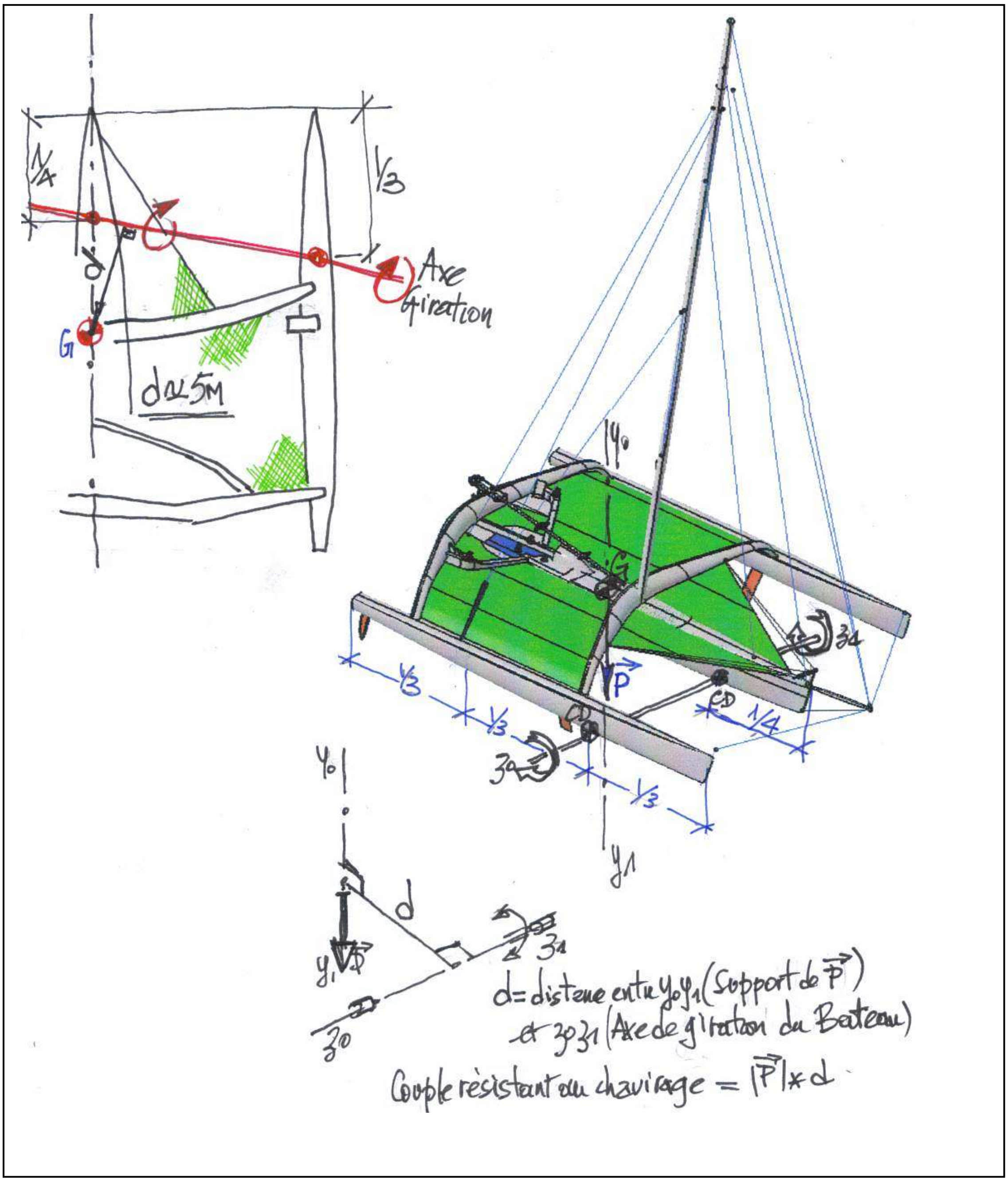
- A point on the underwater part of the outrigger (1/3) of the overall length from the bow. The foil is entirely deployed; the centre of lateral resistance of the outrigger in this trim is relatively deep.
- A point on the underwater part of the main hull (1/4) of the overall length of the hull.

The parameter the easiest to calculate is the couple resisting capsize; it is calculated as in hypothesis Nº1 which is the product of the mass of the multihull times the lever arm (GZ). The GZ is no longer transversal as in hypothesis Nº1; it corresponds to the horizontal distance between the centre of gravity of the multihull and the axis of rotation defined above. For a 60' this distance is of the order of 5m.

The couple resisting capsize is therefore approx equal to:

5800 x 5 = 29,000 $DN_x m$

One remarks simply that the couple is 42% smaller than that corresponding couple resisting transverse capsize calculated in the hypothesis Nº1 (50639DN_xm).



The addition of 800 kg of water ballast increases the couple by 14% (33,000 DN_xm). Which we find is 53% of the couple provoking transverse capsize).

This couple depends essentially on the position of the axis of rotation of the multihull, which depends on the waves, the boat movements, and the instant in which the foil stalls.

All these parameters are not quantifiable. If the centre of pressure moves back 1m (5.5% of the LOA) leveled with the outrigger and the centre hull, the couple resisting capsize reaches 23,200 DN_xm, being 46% of the same couple in transverse stability.

We easily perceive, and the reality of capsizes confirms, that this configuration (sailing off the wind at high speed), is the origin of capsizes. The potential physics of resistance to capsize of a multihull is represented by the couple resisting capsize. In this couple the only element known and constant is the boat's mass, the arm of the lever remains relatively uncertain.

The equation reads:

Couple resisting capsize	>	Couple created by the wind pressure on the sails	+	Restoring couple due to the accumulated energy (effect of the angular inertia, which is a function of the masses in motion and their accelerations).

It remains for a skipper (or an architect, or a system of measuring), to check that this equation is always true…

Jean Sans
10/05/2006