"F3 Floats": Monohull sailboat with small floats - an exploratory study

Jean-François Masset - July 2020 jfcmasset@outlook.fr

Introduction

The starting point of this study is the current Figaro 3 equiped with retractable foils, and the idea of replacing the foils with streamlined 3D bodies, i.e. replacing dynamic lift by an archimedean one. This is imagined for a more cruising objective of the Figaro 3 aiming at a gain of performance and less heel angle in the moderate and usual speed ranges for the average sailor (6-7 Kts upwind, 10-12 Kts downwind). For these speed ranges, a streamlined 3D body when submerged can provide a buoyancy lift significantly contributing to the righting moment with a good Lift/Drag ratio, i.e. can be a valid alternative to a foil more oriented and optimized for downwind high speeds. The purpose of this exploratory study is to identify and quantify this alternative option.

For this, an early stage project of the ship, the so-called **F3**, of dimensions and lines inspired by those of the Figaro 3, is established with 2 versions tin order to make comparisons with identical light displacement :
- a version with a system of 2 retractable floats (typ. 300 liters each), with an estimated total mass of typically 180 kg. Floats of 200 liters (120 kg) and 400 liters (240 kg) are also considered to show the influence of the volume.
- a version without floats and with 180 kg of additional ballast for the keel-bulb

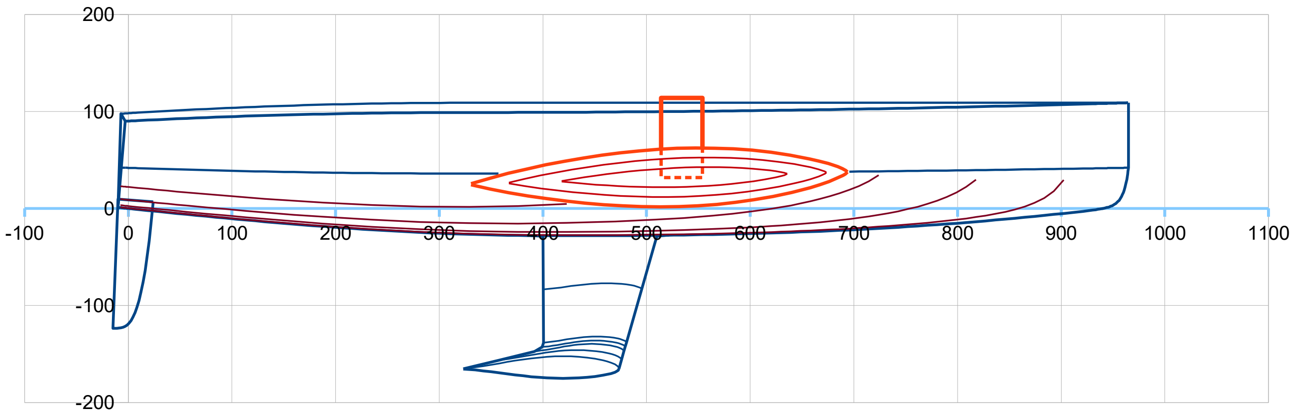
Summary :

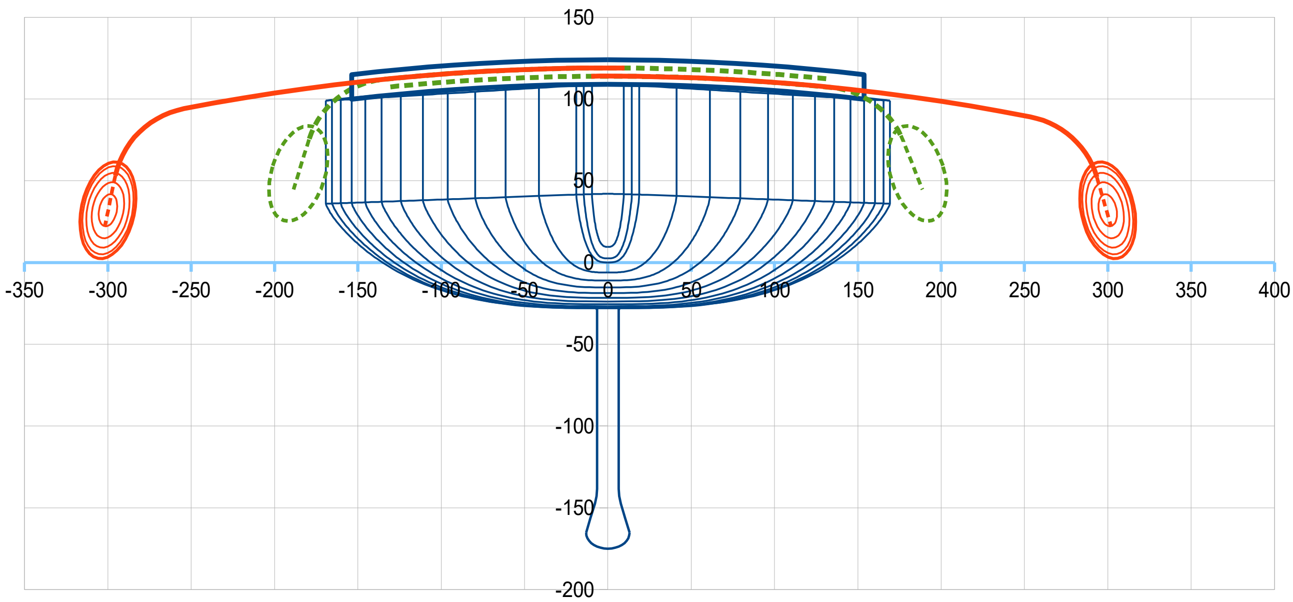
1. Presentation of the two F3 versions

The two versions have the same hull inspired by the Figaro 3 one, and the same light ship displacement (3250 kg) a little higher than that of Figaro 3 (2900 kg) for a more race-cruising program with a cabin offering a minimum of accommodation. The DLR 109 is still light. In the same spirit, the draft is limited to 1.75 m, with a fin keel-bulb in cast iron. The F300 float showed in the views here below is the one used for the first run of the VPP calculations, with a length of 3.64 m and a volume of 301 liters. The mass of the float system, with including the support arms (ie the « akas ») and the common sliding structure for storage/deployment of these arms (the common « drawer »), is estimated at 180 Kg. For a fair comparison at same light ship displacement, the version without floats has the 180 kg available in the form of extra cast iron in its keel-bulb.

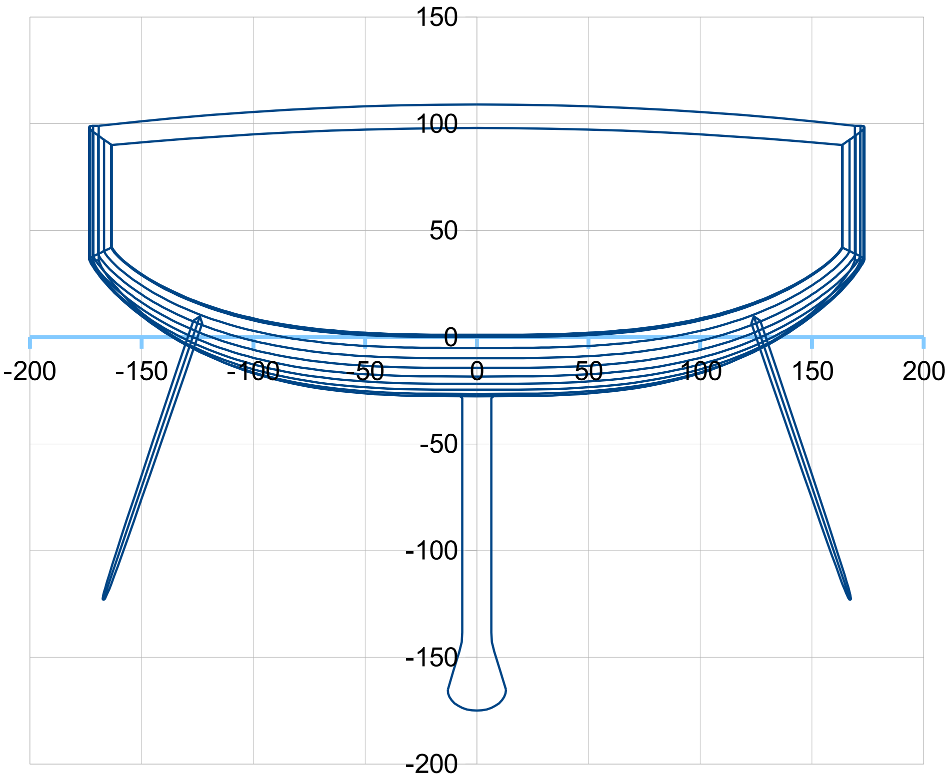
Version F3 version with F300 (i.e. 300 liters) floats :

Lo.a. : 9,75 m   Lwl = 9,40 m   Bhull = 3,47 m Draught = 1,75 m ; Ligh ship displacement = 3250 kg ; Ballast : 1012 kg

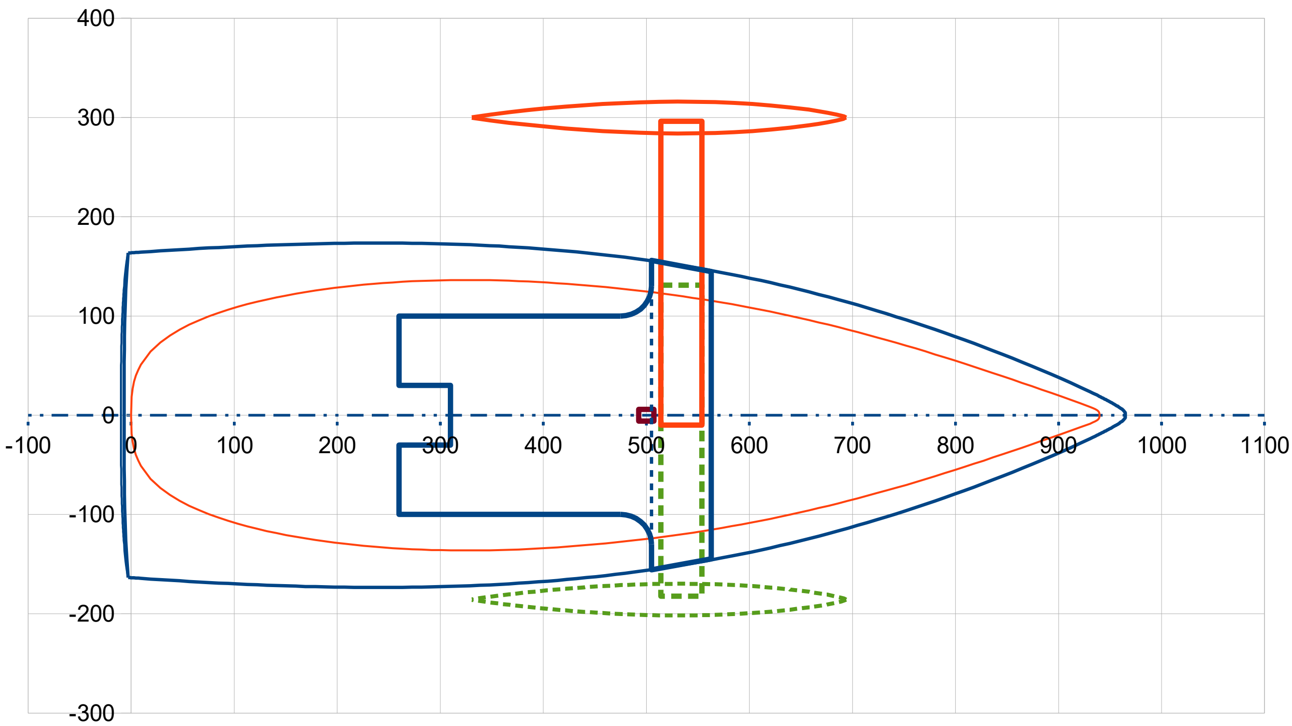


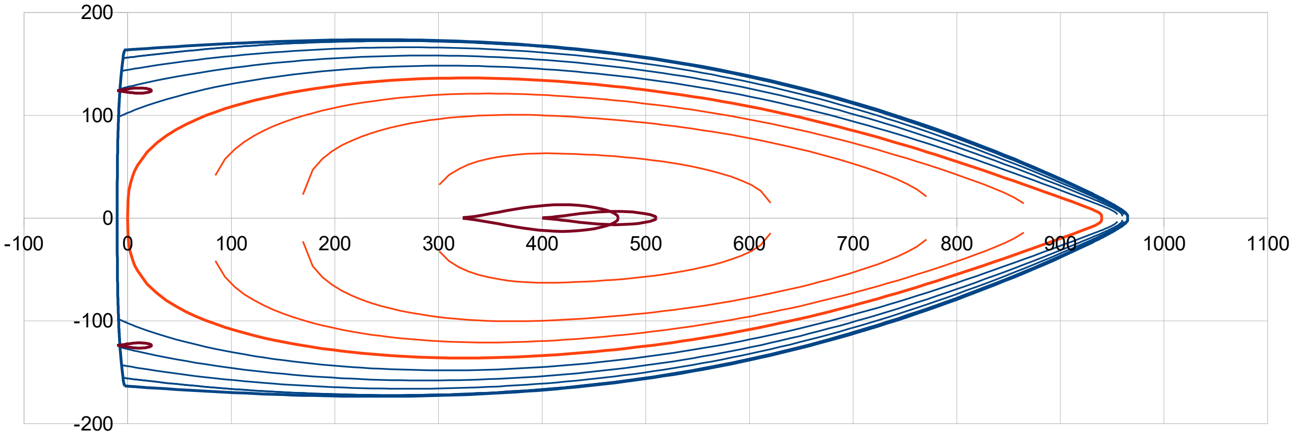


Floats as drawn : L 3,635 m ; Ellipsoide 3D body of section max. Da 0,60 m x Db 0,32 m
Volume 0,3015 m3 ; **Sw 3,683 m2** ; Slight nose-up trim, of + 2°



When the floats are in the retracted position (**drawn in green**), their lowest point is at **Z + 25 cm** / water and the overall width of the ship in the marina will be only **Boa: 4,07 m**.

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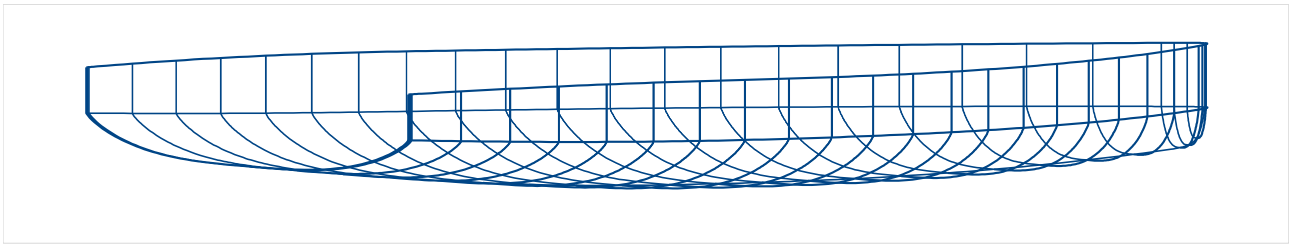
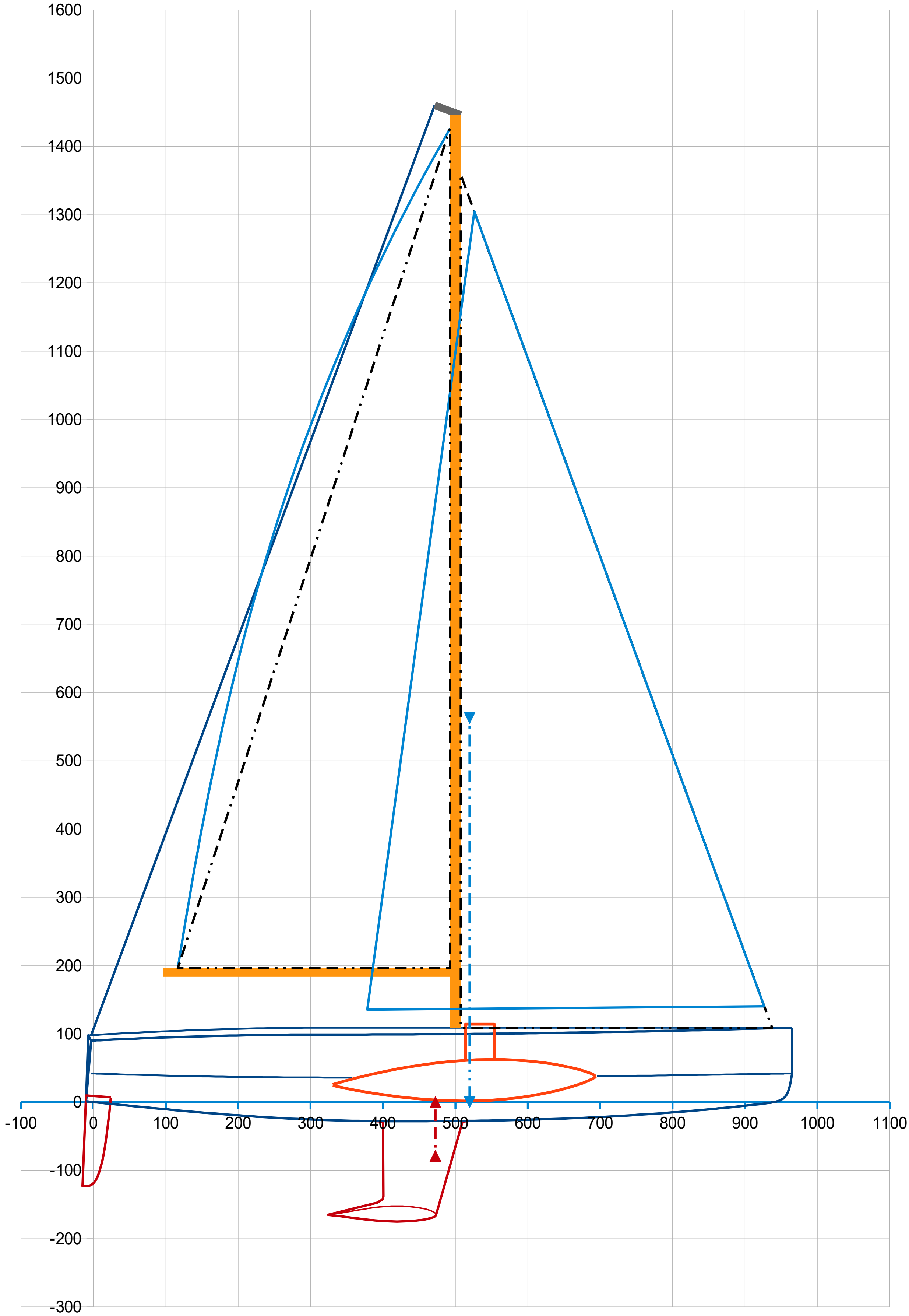


Sails area for an upwind sailing : Mainsail 29 m2 Jib 33,4 m2 >> Total 62,4 m2



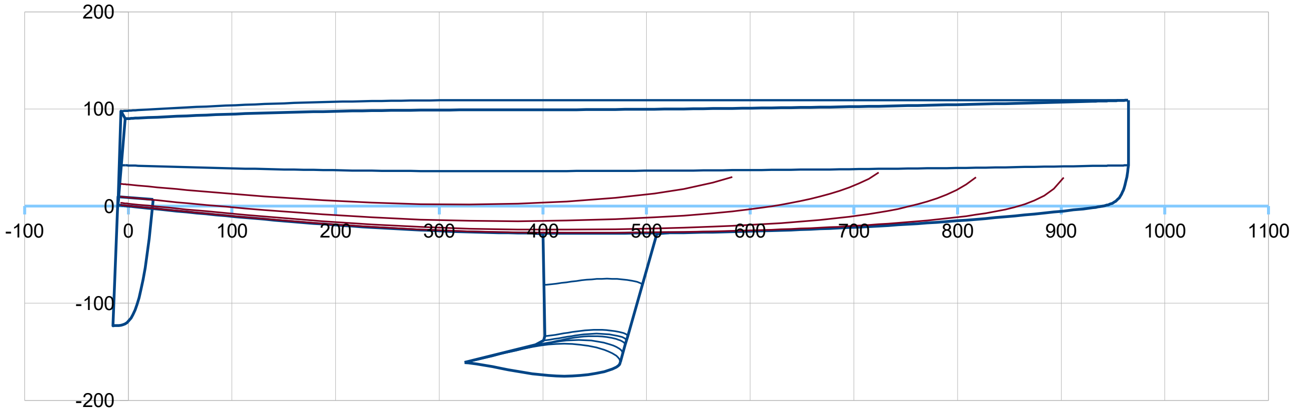
Hydrostatics data :

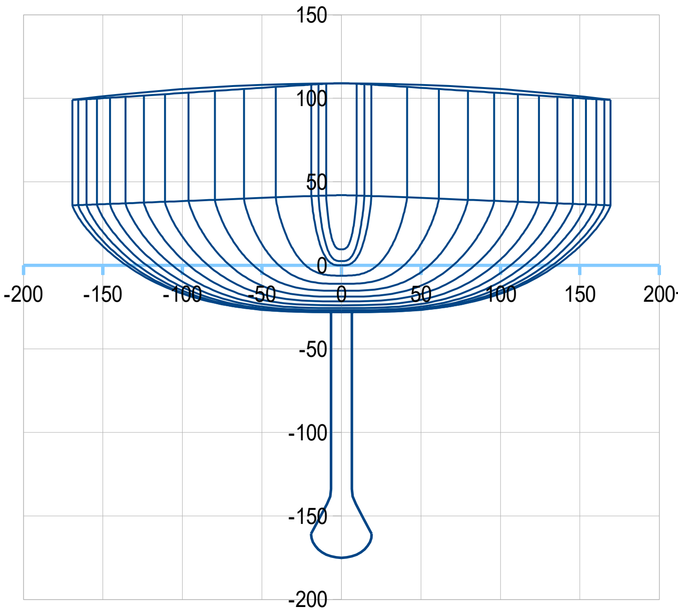
2.1 Hull															
Loa (m)	9,75			Lwl (m)	9,40					> Hull speed (Knots)	7,5		at Froude 0,4		
>> ft	31,99				30,84										
Boa (m)	3,47			at X (% Lwl)	26,0			Bsheer (m)	3,47			at X (% Lwl)	26,0		
>> ft	11,38														
Bwl (m)	2,72			at X (% Lwl)	35,0			> Bwl / B	0,785						
>> ft	8,94									Freeboards (m) >	Aft		Midship		Fore
Tc (m)	0,28			at X (%Lwl)	50						0,90		0,99		1,09
>> ft	0,92									>> ft	2,95		3,25		3,58
		Displacement at H0 (m3)	3,01457			at LCB (m)	4,324			LCB (%Lwl)	46,00			ZCB (m)	-0,103
		>> lbs	6812			w. seawater	1025		kg/m3					>> ft	-0,34
Cp (%)	56,58														
Sf (m2)	18,58			at Xf (m)	4,073			Xf (%Lwl)	43,33					>>> Xc – Xf (%Lwl)	2,66
>> ft2	199,94			>> ft	13,36										
Angle Freeboard/Half beam			30,3		(°), at section C4 (40% Lwl)										
Sw (m2)	18,98			>Sw/D^(2/3)	9,09										
>> ft2	204,26														
Shull (m2)	42,03			at X (m)	4,340			Z (m)	0,165						
>> ft2	452,43			>> ft	14,24			>> ft	0,54						
Sdeck (m2)	25,90			at X (m)	3,928										
>> ft2	278,80			>> ft	12,89										
2.2 Keel															
Vol. keel(m3)	0,08767			at X (m)	4,560			X (%Lwl)	48,51			Z (m)	-0,791		
Mass keel(kg)	639,98			>> ft	14,96							>> ft	-2,60		
>> lbs	1411														
Vol. Bulb(m3)	0,05100			at X (m)	4,236			X (%Lwl)	45,06			Z (m)	-1,597		
Mass bulb(kg)	372,33			>> ft	13,90							>> ft	-5,24		
>> lbs	821														
Draft oa (m)	1,75					Sw (m2)	3,57					Sxz (m2)	1,36		
>> ft	5,74					>> ft2	38,47					>> ft2	14,59		
CLR (m)	4,725			CLR (%Lwl)	50,26	*CLR = Center of Lateral Resistance*									
>> ft	15,50	method : keel profile extended to the waterline, CLR at 25% chord and 45% draft oa													
2.3 Rudder(s)															
Number	2														
Volume (m3)	0,01731			at X (m)	0,054			X (%Lwl)	0,57			Z (m)	-0,465		
Sw (m2)	1,60			>> ft	0,18							Sxz (m2)	0,39		per rudder
>> ft2	17,25											>> ft2	4,15		
2.4 Hull + Keel + Rudder(s)															
		Displacement at H0 (m3)	3,17055			at LCB (m)	4,306			LCB (%Lwl)	45,80			at ZCB (m)	-0,148
		(kg)	3250			>> ft	14,13							>> ft	-0,48
		>> lbs	7165												
		, of wich Ballast (kg)	1012			at Xg (m)	4,441			Xg (%Lwl)	47,24			at Zg (m)	-1,088
		>> lbs	2232			>> ft	14,57							>> ft	-3,57
		>> % Ballast	31,1												
		Sw (m2)	24,15			>Sw/D^(2/3)	11,19			Lwl/D^(1/3)	6,40				
		>> ft2	259,98							**DLR**	**109**		*M(lbs/2240)/(Lwl(ft)/100)^3*		
2.5 Data from the mass spreadsheet															
Light boat:		**M (kg)**	**3250**			**at Xg (m)**	**4,244**			**Xg (%Lwl)**	**45,15**			**at Zg (m)**	**0,614**

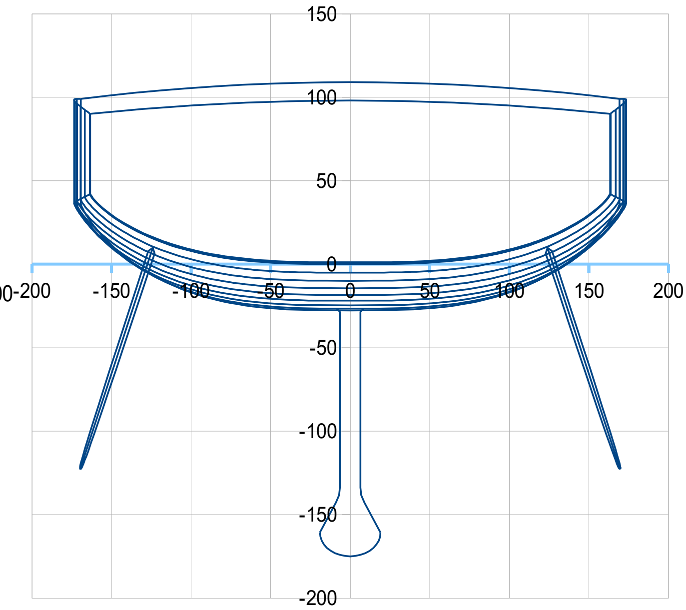
F3 version without floats, with a keel-bulb weight increased of 180 kg at same displacement :

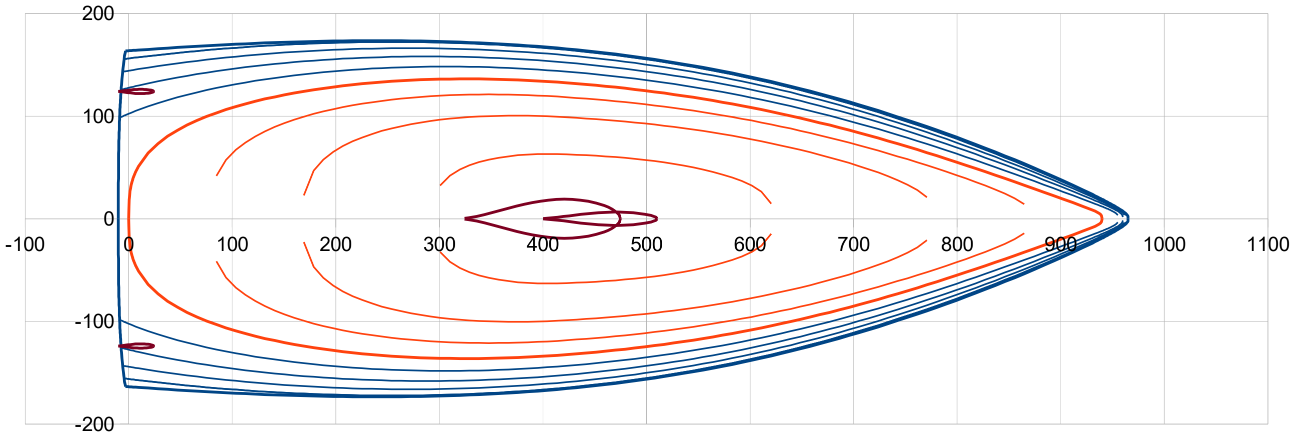
Lo.a. : 9,75 m Lwl = 9,4 m Bo.a. = 3,47 m Draft = 1,75 m ; Displacement light ship = 3250 kg ;
Ballast **: 1194 kg**

>>> The extra ballast lowers the ZcG from 0,61 m to 0,46 m, all other things being equal.









2. Choose of a first float design to initiate the performance study

To explore the concept, the approach consists to proceed in several steps :

- at first to define a float volume a priori >>> 300 liters, named **F300** in the following of the study
- tp search an optimal shape to minimize its drag taken into account the various predictable configurations of heel and speed (upwind as well as downwind) and consequently of sinkage for the float,
- to compare the performances when sailing upwind or downwind with a VPP.
- To test the volume influence by repeating the approach with two other values : 200 liters , 400 liters

The float can be either partially immersed or totally immersed and then more or less deep with regard the water surface, all that at either slow speed (upwind) or fast speed (downwind). The two components of the drag, wave drag and friction drag, thus find themselves at stake and in variable fractions (in annex 1 are detailed the formulations involved for this evaluation). A first very preliminary computation with the VPP allows to determine the typical cases for the float which can be used as reference to base the search of an optimal shape :

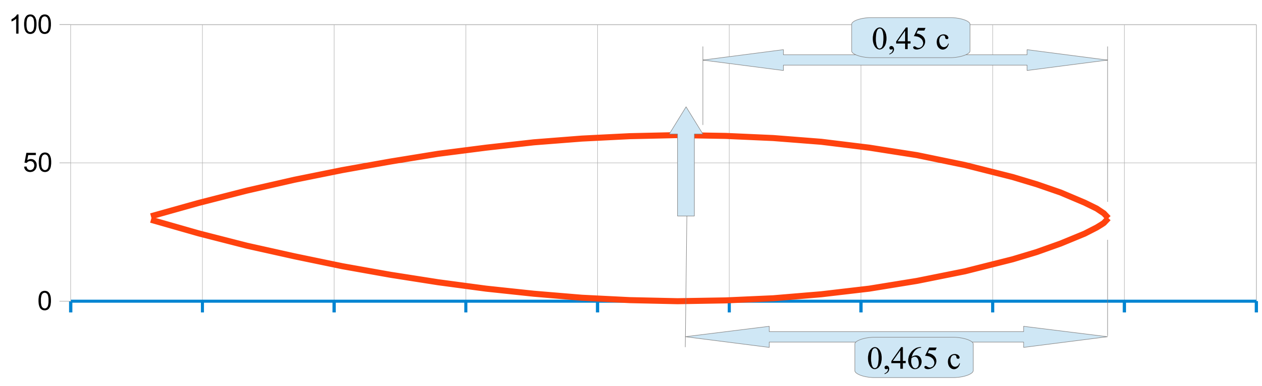
Upwind :

- heel of 13° and boat speed 6 Knots
- heel of 19° and boat speed 6,5 Knots
- heel of 23° and boat speed 6,6 Knots

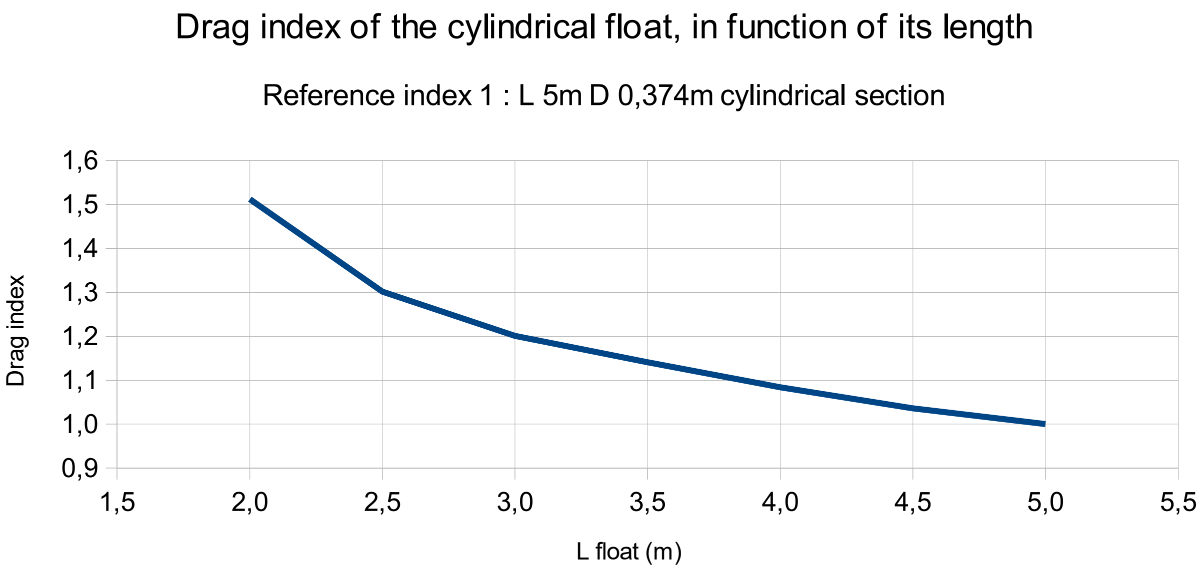
Downwind (twa 140°) :

- heel of 8° and boat speed 9 Knots
- heel of 18° and boat speed 12 Knots
- heel of 23° and boat speed 14 Knots

The float shape can be defined by its longitudinal profile and its maxi section. The longitudinal profile is derived from a Naca 4digits type with abscissa x at power 1,48, so positioning the maxi section at 0,45 of the chord c corde and the volume center at 0,465 c. It is an a priori choice (a usual basic approach for a 3D streamline body) and preliminary, the optimal shape of the longitudinal profile should also take into account the pressure centre with speed and the twist moment generated in the « aka » (these considerations are evoked in paragraph 7).

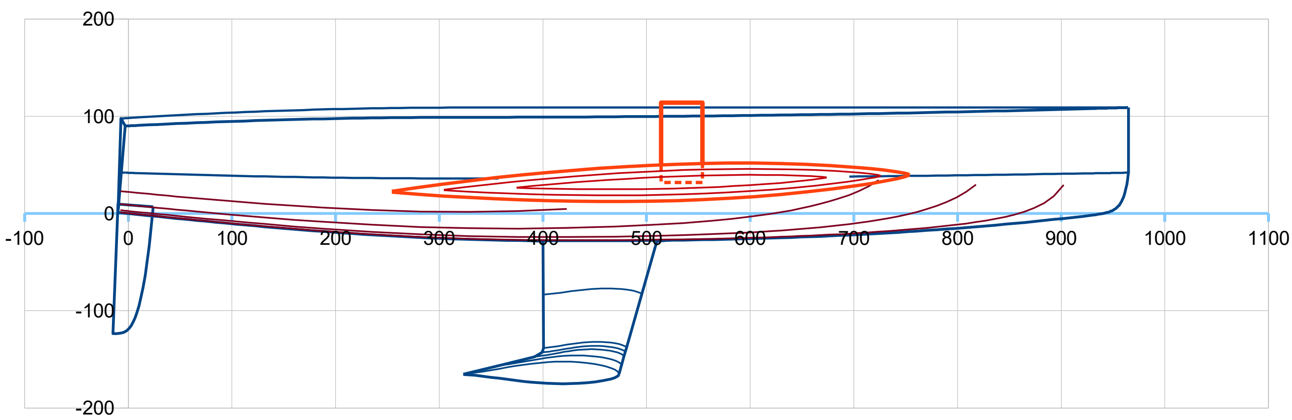


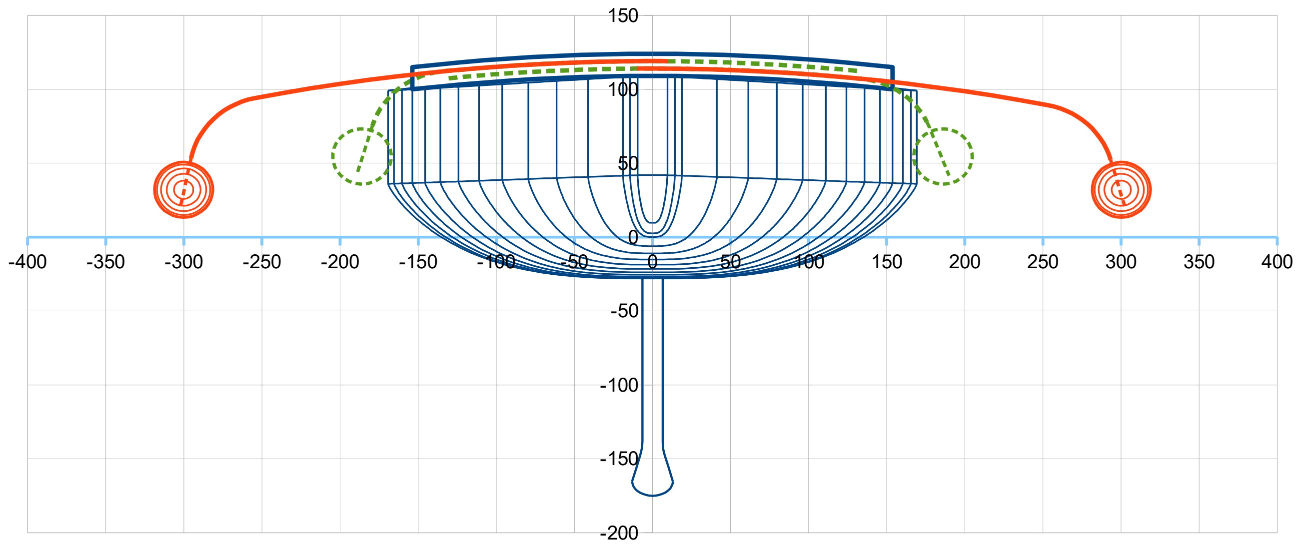
That approach so defined, the first iteration consists to estimate the drag with a float of cylindrical section and by varying its length from 2m to 5m at constant volume (by considering 5m is a practical limit for the intended mounting).
>>> here after results take into account of the average of drags when upwind and drags when downwind taken at equal part and made adimensionnal by putting 1 as index for the average drag obtained with a 300 liters float of 5m of length and 0,374 m of diameter :

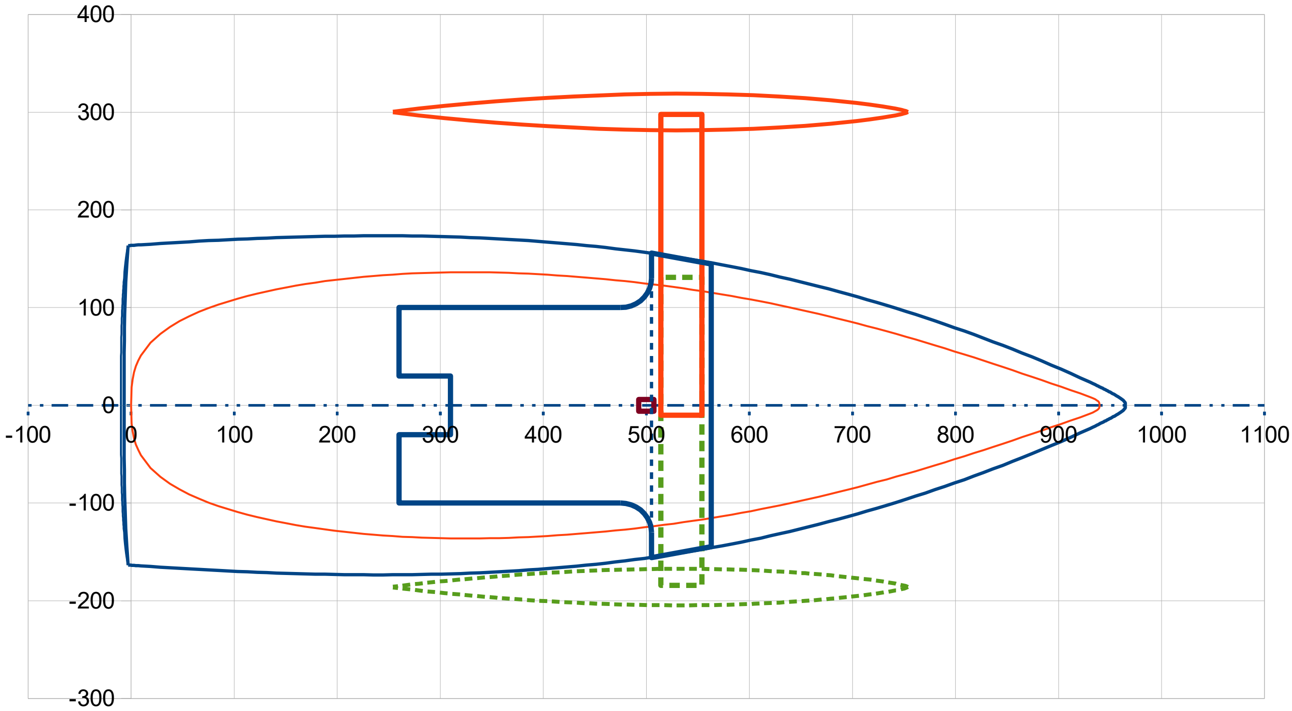


It is found that the average drag decreases continuously with increasing length, resulting from the fall of the wave drag component despite the increase in the wetted surface.

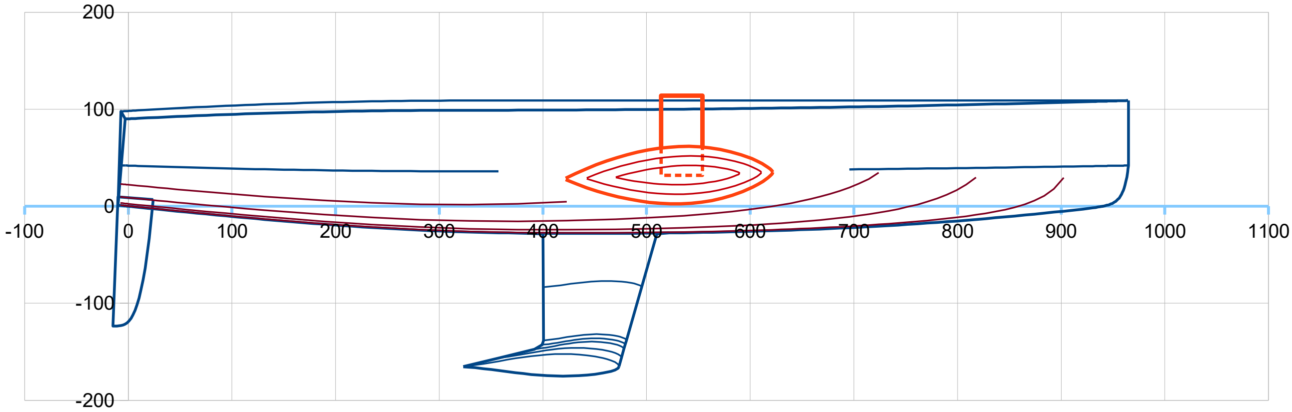
Extreme configuration : with **L 5m and D 0,374m , leading to the minimum drag (index 1)**

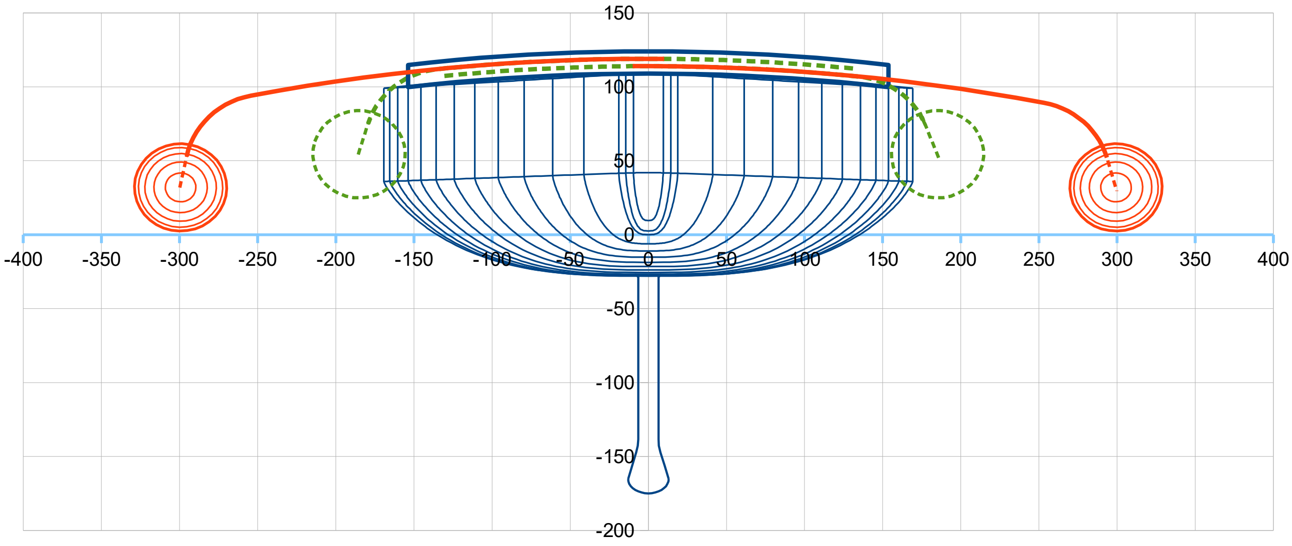


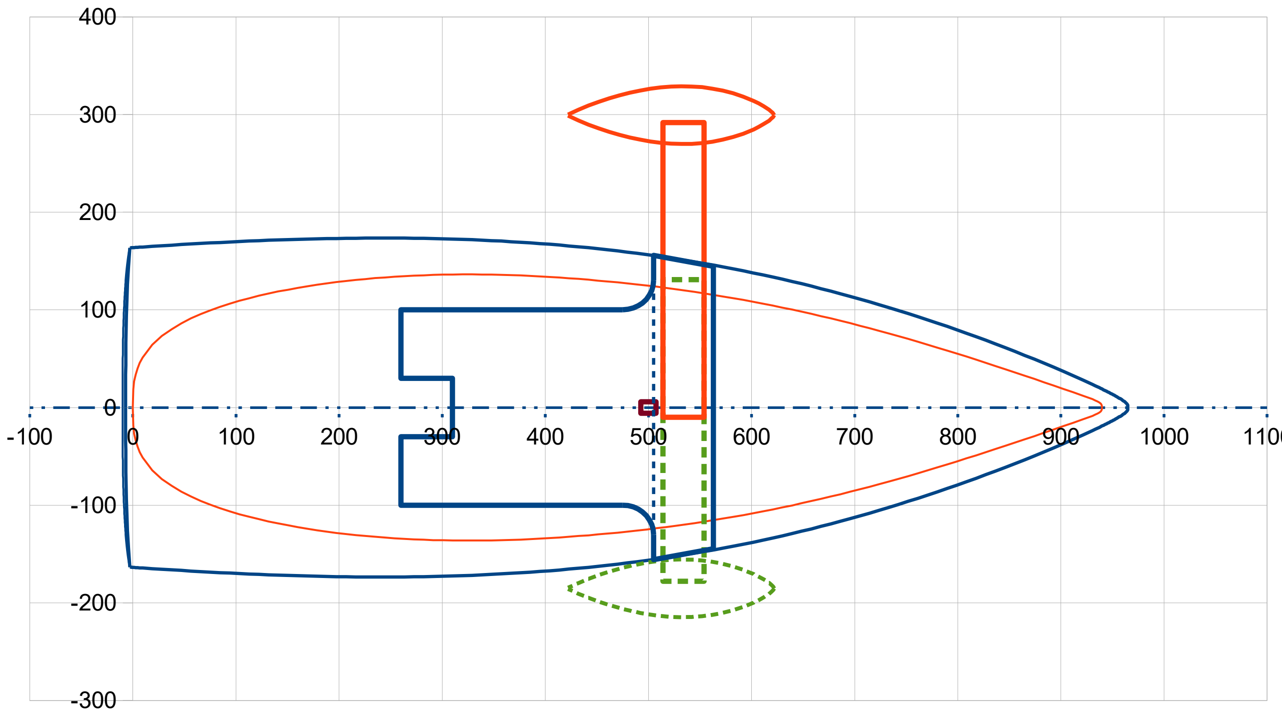




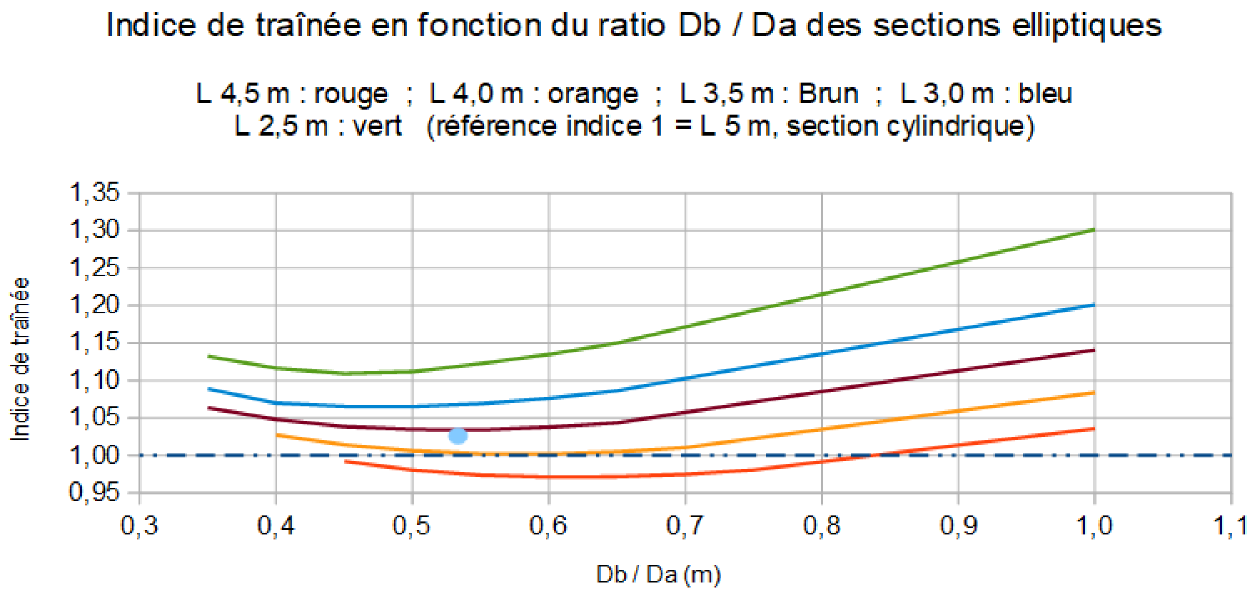
With L 2m et D 0,591m, at the contrary we obtained the maximum drag (index 1,5) :







Due to the importance of the wave drag in most cases, it is logical to search another shape which can minimize this component without increasing too much the wetted surface : a float with an elliptical section, of diameters **Da** increased following the height and of **Db** decreased following the width, since the width **Db** influences the squared part of the wave drag component whereas the wetted surface evolves more slowly with the ratio **Db/Da**. With also the objective to reduce significantly the length of the float but at index drag still close to 1 : L 5m is estimated too important, exposing to bending moments due to overhangs. And the objective to mitigate, with a shape more « flat » than a cylindrical one, the forward displacement of the pressure center generating a twist moment in the « aka ». This second iteration so address a shorter range of lengths 2,5 m – 4,5 m, and ratios **Db /Da** of 0,35 to 1,0. Results, still considering the drag index 1 as reference (dashed-dot line) :



L 4,5 m gives the lowest mean drag : Index 0,971 with Db/Da = 0,6 , but that still means a rather great length for the floats.

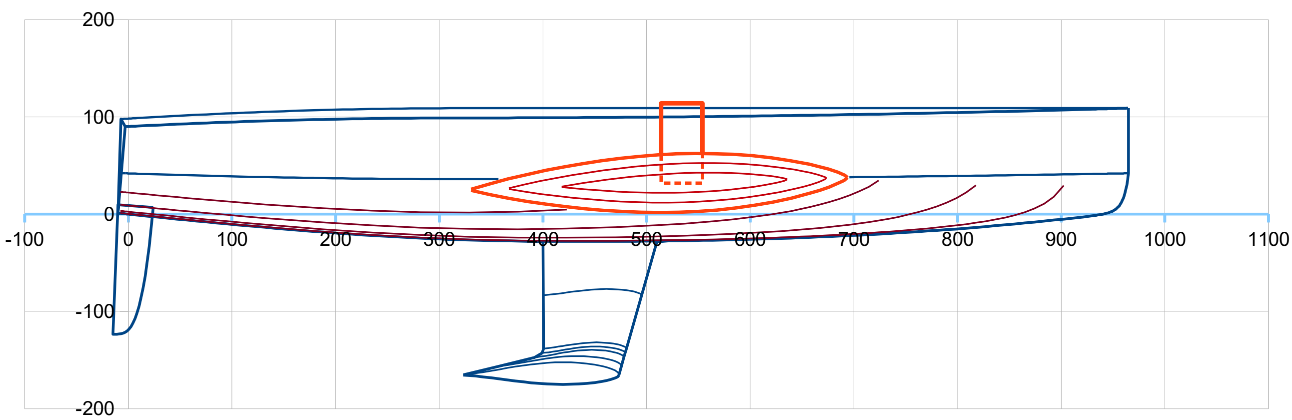
L 4,0 m gives a minimum drag of 1,002 with Db/Da = 0,55 and 0,60

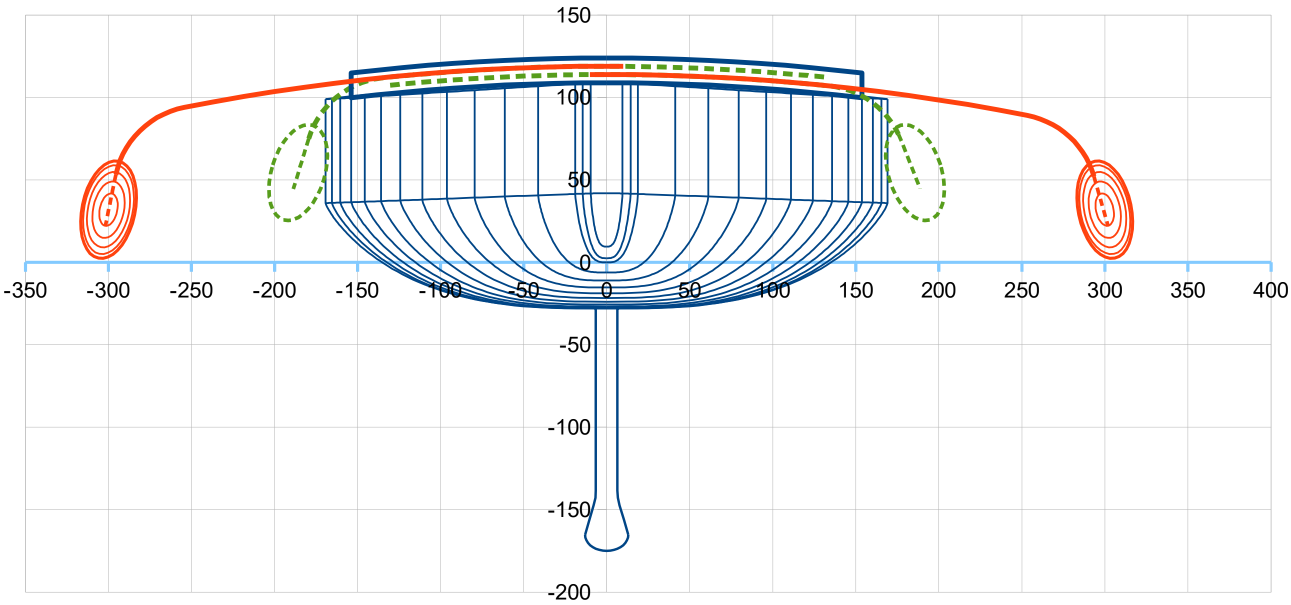
L 3,5 m gives a minimum of 1,034 with Db/Da = 0,55 , this length becomes a reasonable trade-off

L < 3,5 m : the drag becomes penalizing in reference with the L 5m cylindrical case.

>>> finally, choice of :

F300 : L 3,635 m Db 0,32 m Da 0,60 m (Db/Da = 0,533) Volume 0,3015 m3 Sw 3,683 m3 , for a drag index of 1,026





3. Righting moment and wetted surface with heel

These two quantities function of the heel are necessary input for the VPP : they are estimated from the hydrostatic balance of the heeled hull for the two versions with and without floats. The hydrostatic equilibrium here means equality weight/buoyancy and equality of the longitudinal center of the boyancy (LCB) with the one of the center of gravity (XcG). It is of course an approximation of the real equilibrium in dynamic, but sufficient to evaluate these two quantities RM and Sw (Hull + leeward float) and their evolution with the heel. These two functions RM et Sw are then input in the VPP.

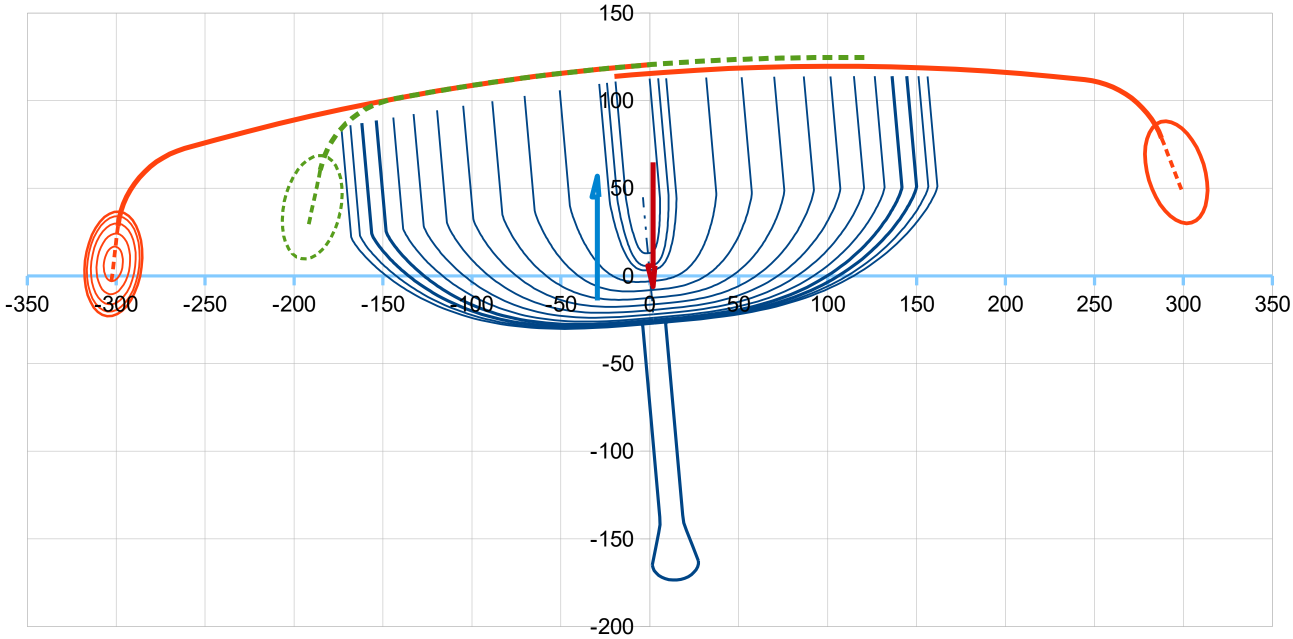
The step prior to studying these balances with a heel is to estimate the center of gravity of the light ship + a standard minimum payload (160 Kg, i.e. 2 people seated in the wind). This leads to the following data to take into account :

	With floats	Without floats
Light ship (kg)	3250	3250
Xg (m)	4,24	4,24
Yg (m)	0	0
Zg (m)	0,61	0,46
Payload (kg) (Crew seated windward)	160	160
Xg (m)	2	2
Yg (m)	1,6	1,6
Zg (m)	1,2	1,2

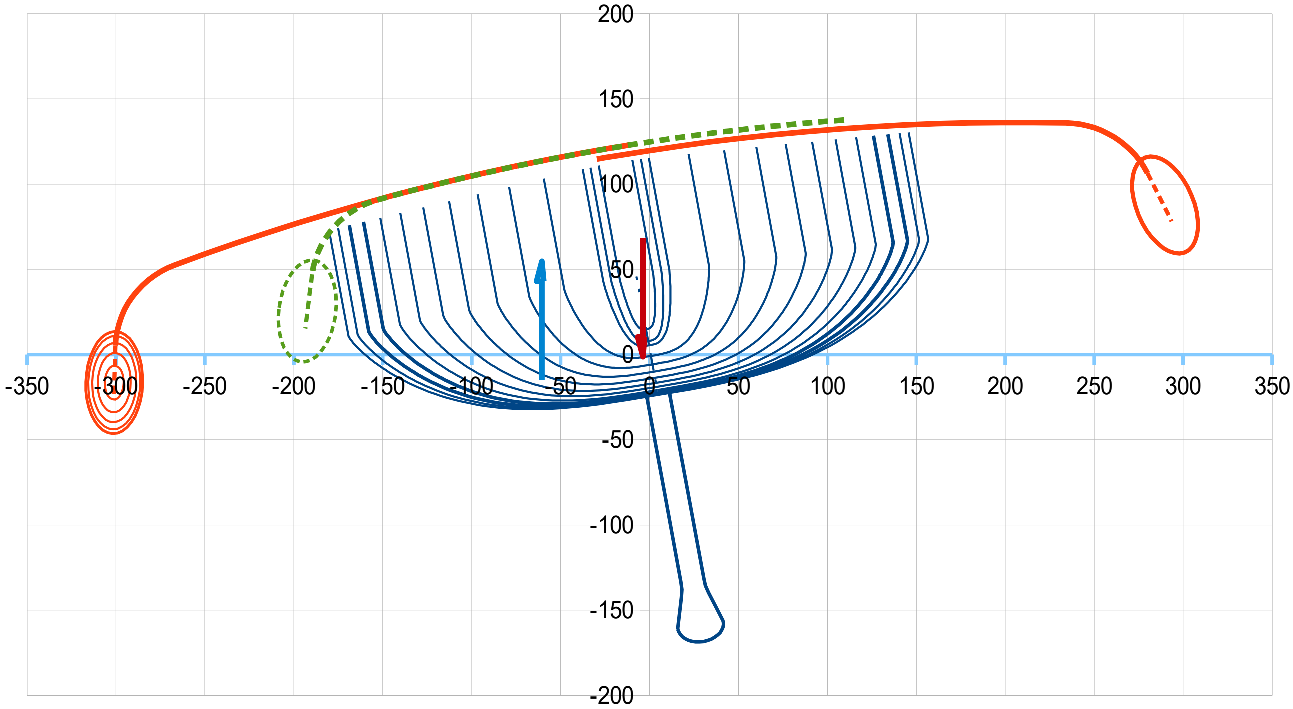
The volume of the support arm (the « aka »), preliminary assumed a Naca 4digits profile or equivalent, of chord 400 mm and thickness 9 mm, when this arm becomes immersed due to the heel, is also taken into account.

>>> computation of the equilibrium with heel = 5° to 40° with a step of 5° , with the F300 :

With heel = 5°, F300 deployed (drawn in red) >>> immersion of 34% of the float volume
Trim : + 0,30° ; RM 10,507 kN.m ; Sw hull 19,18 m2 ; Sw float 1,42 m2

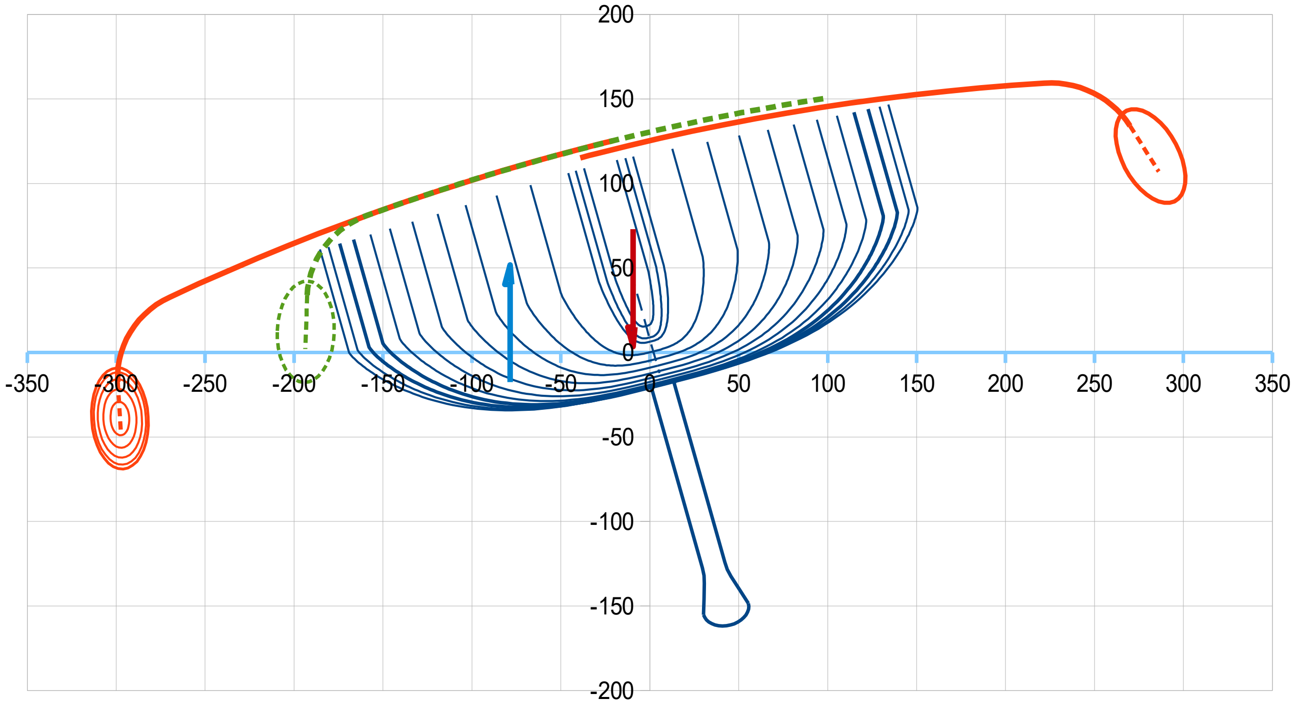


With heel = 10°, F300 deployed (drawn in red) >>> immersion of 84,5% of the float volume
Trim +0,17° ; RM 18,972 kN.m ; Sw hull 18,10 m2 ; Sw float 2,85 m2



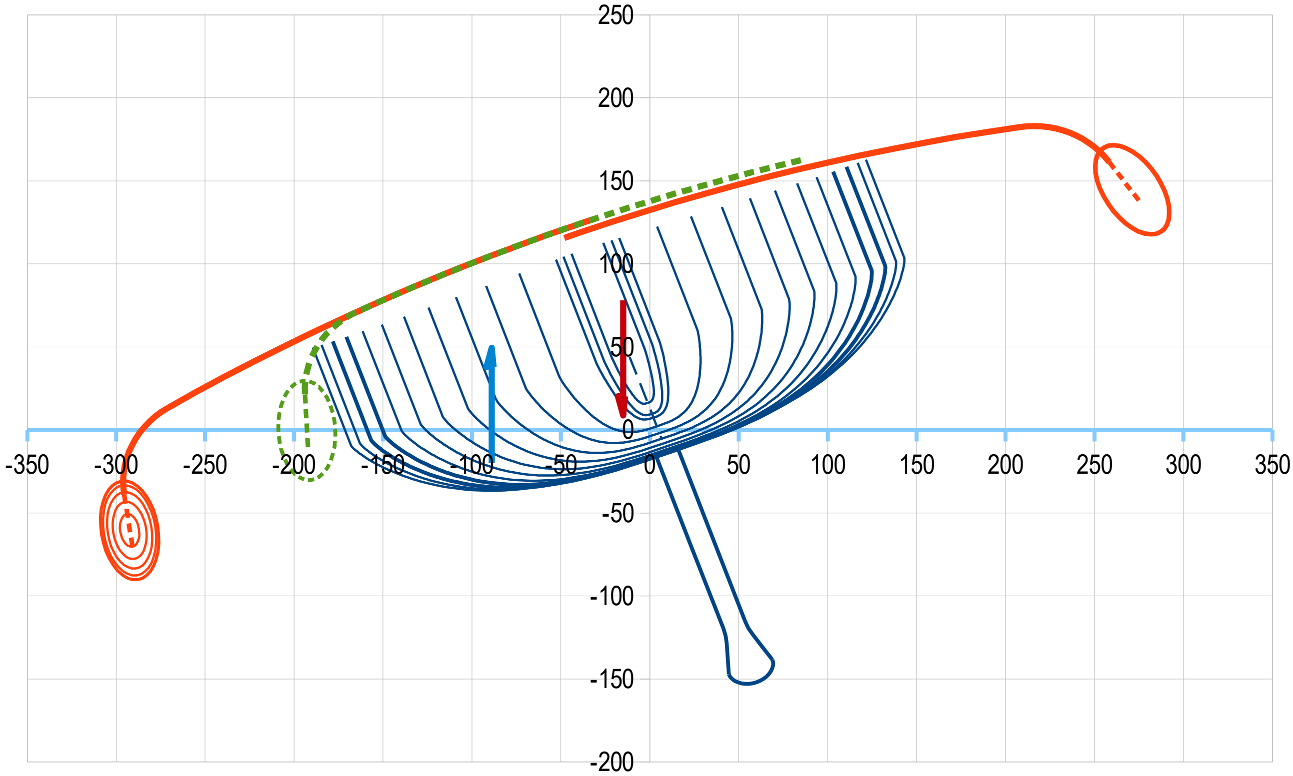
With heel = 15°, F300 deployed (drawn in red) >>> full immersion complète of the float

Trim -0,18° ; RM 23,155 kN.m ; Sw hull 17,01 m2 ; Sw float 3,68 m2



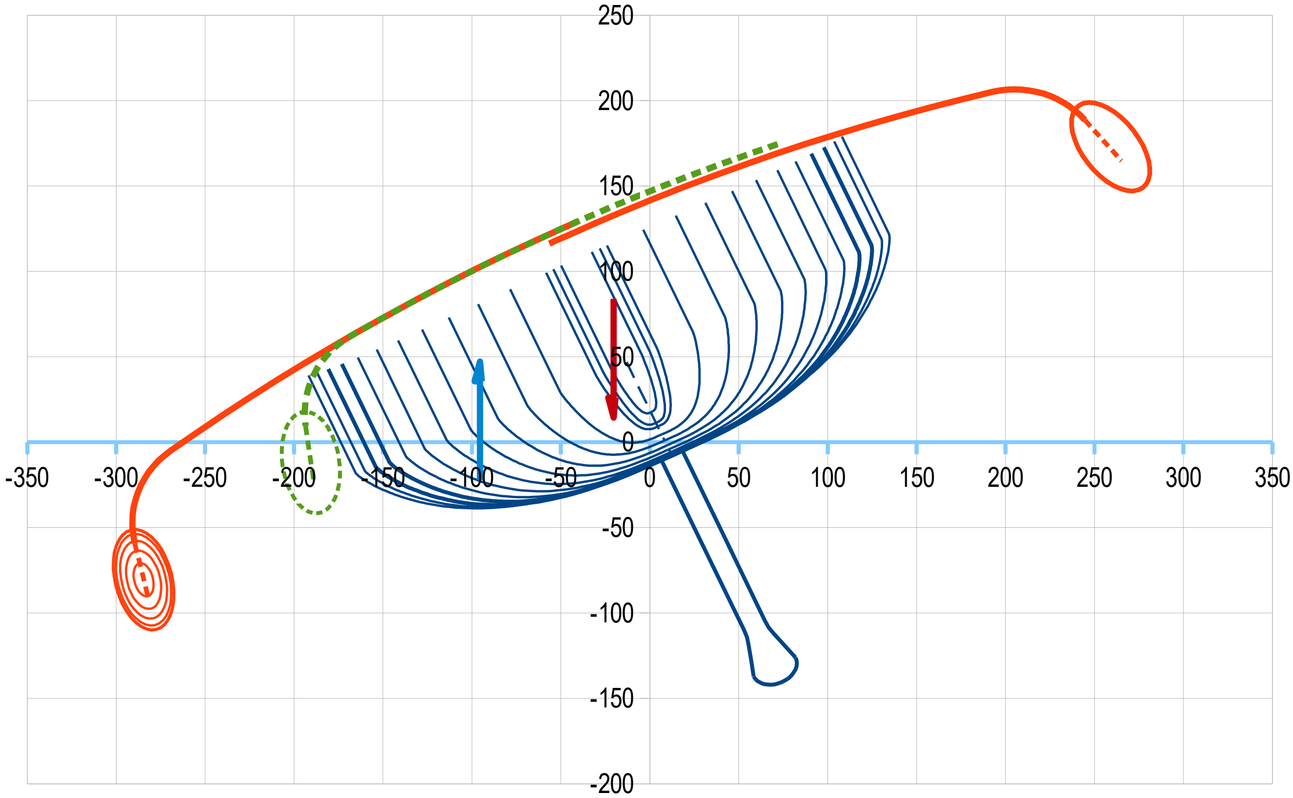
With heel = 20°, F300 deployed (drawn in red) >>>

Trim -0,67° ; RM 24,735 kN.m ; Sw hull 15,54 m2 ; Sw float 3,68 m2



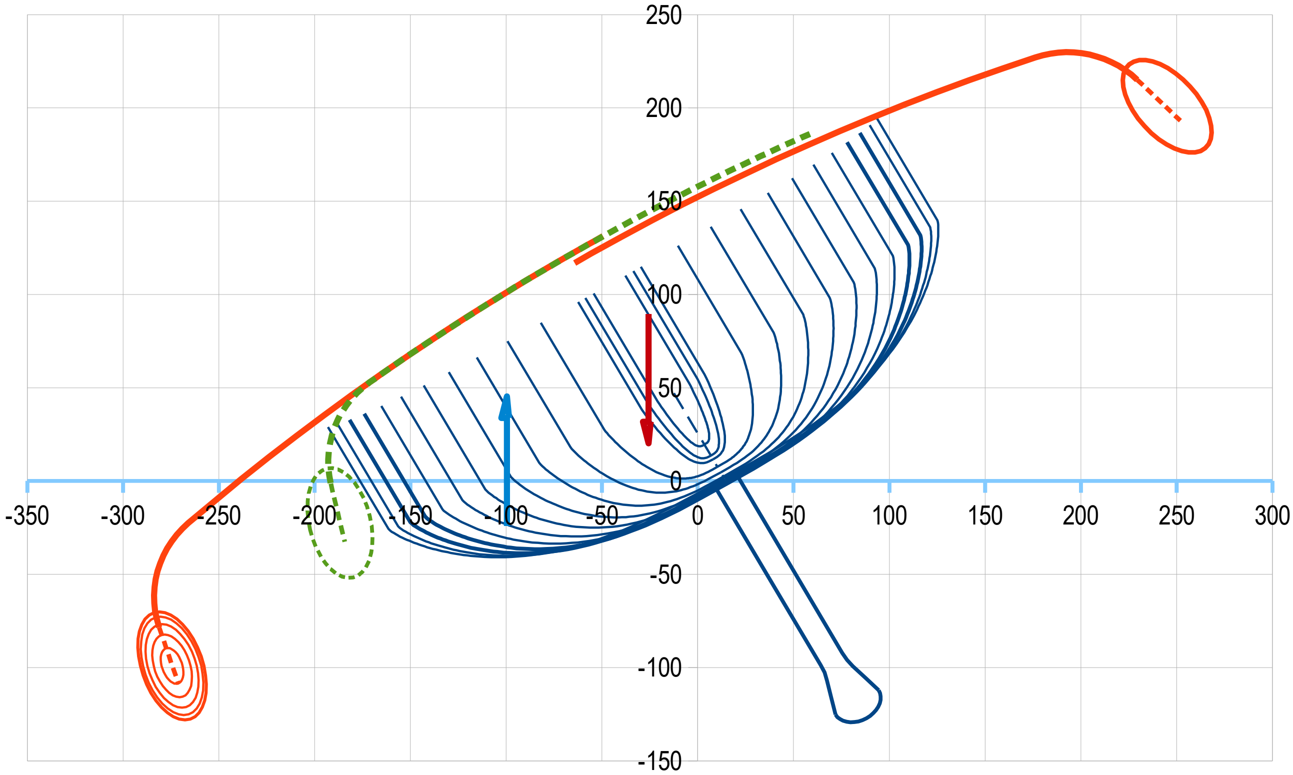
With heel = 25°, F300 deployed (drawn in red) >>>

Trim -1,21° ; RM 25,145 kN.m ; Sw hull 14,07 m2 ; Sw float 3,68 m2



With heel = 30°, F300 deployed (drawn in red) >>>

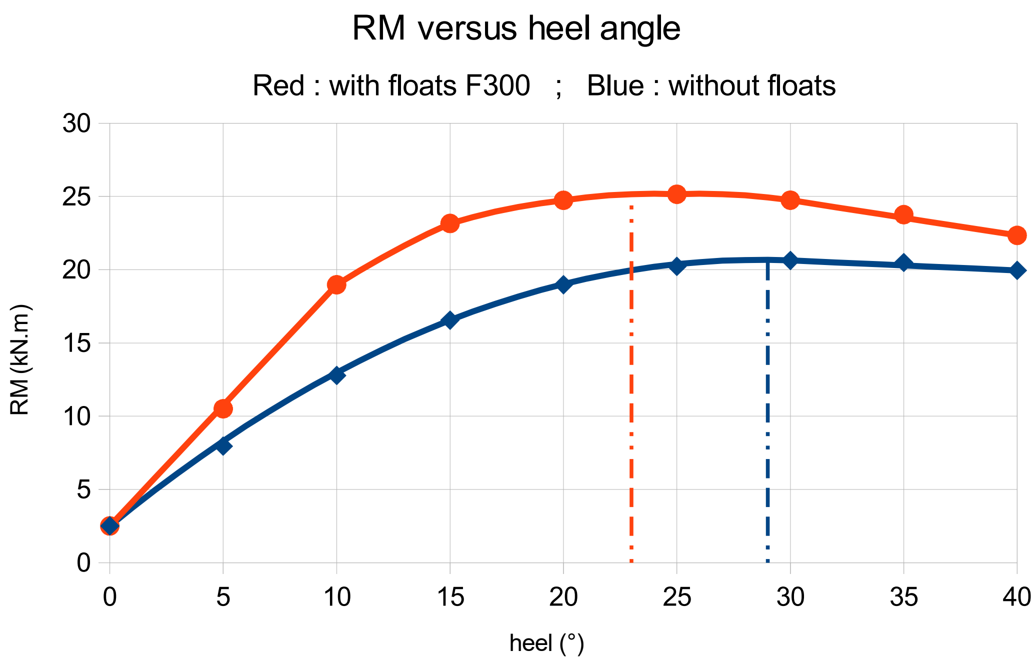
Trim -1,80° ; RM 24,742 kN.m ; Sw hull 12,69 m2 ; Sw float 3,68 m2



With heel = 35° , F300 deployed
>>> Trim -2,47° ; RM 23,755 kN.m ; Sw hull 14,20 m2 ; Sw float 3,68 m2

with heel = 40°, F300 deployed
>>> Trim -3,26° ; RM 22,341 kN.m ; Sw hull 14,24 m2 ; Sw float 3,68 m2

, which lead to the following curves for RM and Sw :

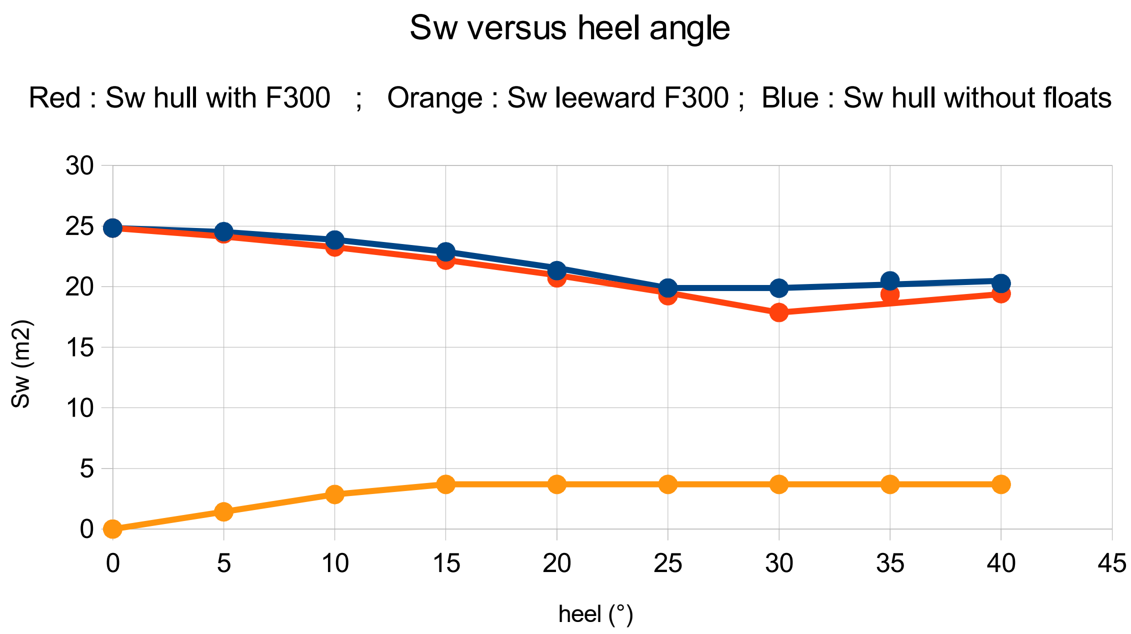


The RM curve with floats F300 is clearly above the one without floats up to at least 40° of heel. Its peak is at about heel 24° while the version without floats the RM max is at about heel 30 and for 80 % of the RM max with floats. The VPP here-after shows that, upwind with 14 Knots of wind, before that a sail area reduction is necessary, the heel is about ~ 23° while the one without floats is about ~ 29°. From these respective equilibrium configurations, if a gust of wind happens, the stability reserve up to a heel of 40° (i.e. before the reaction of the helmsman) is in proportion of the area under the RM curve :

- without floats : area from 29° to 40° = 203 deg.kN.m
- with floats flotteurs : area from 23° to 40° = 411 deg.kN.m , so ~ twice.

>>> the resistance to a dynamical overheel up to 40° is twice :

A gust of wind giving an extra heel in dynamic from 29° to ~ 40° for the version without floats (before the helmsman reaction)) will give (at equivalent area under RM curves) an extra heel from 23° to ~ 31° for the version with floats F300.



The wetted surface of the central hull with floats (in red) is little reduced with regard the one without floats (in blue) despite the contribution of the leeward float buoyancy. This is not sufficient to compensate the extra wetted surface due to the float (in orange). But yet, by light winds (when the heel angle is small), it is possible to sail with floats retracted, and then in no or very marginal contact with the water surface, and so mostly avoid this disadvantage.

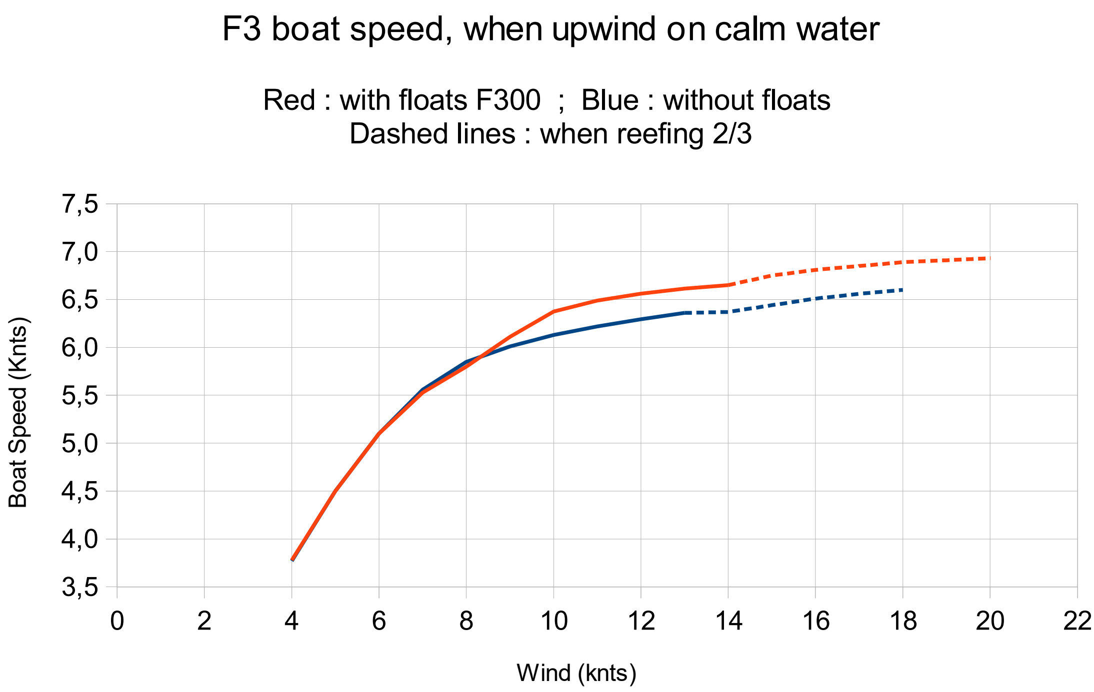
4. Performance comparison when upwind

This comparison is done with a VPP and for the two versions with floats F300 and without floats (and then a ballast increased by 180 kg) , at same light ship displacement and with the same sailplan.

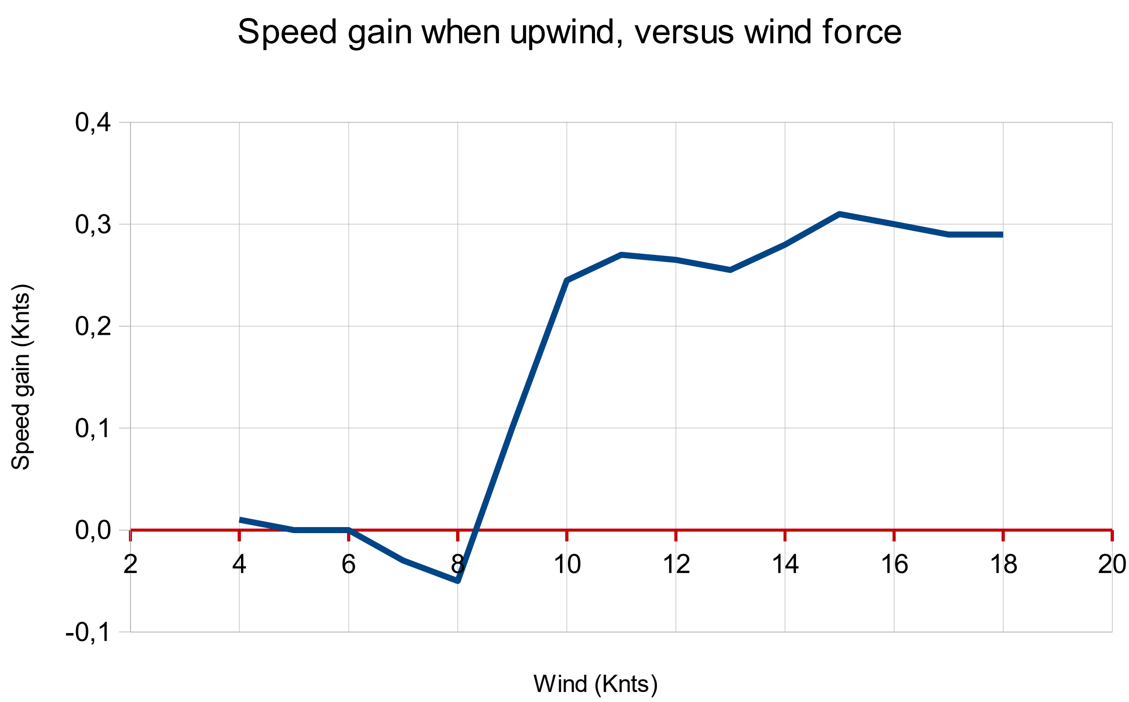
For the version with floats, one consider 2 modes « retracted » or « deployed » :

- with the leeward float retracted (and the windward float maintained deployed), as long as the leeward float is no or marginally in contact with water, i.e. as long as the wind is light enough >>> the VPP shows that it is the most efficient mode up to ~ 8 Knots of wind.

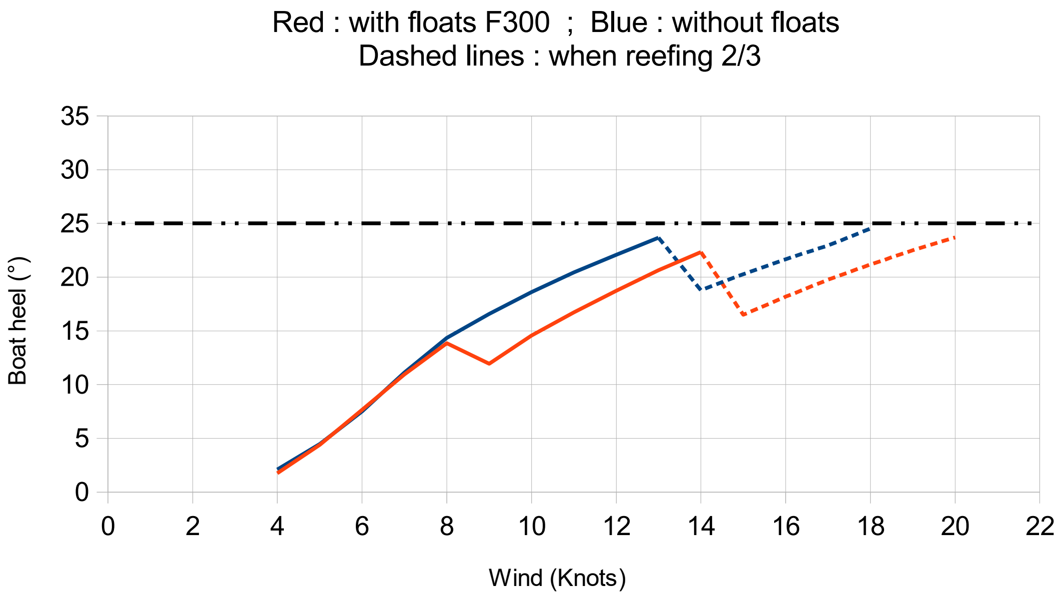
- with the leeward float deployed >>> this mode becomes profitable from 9 Knots of wind.



The transition between the two modes float retracted >> float deployed is around 8 - 9 Knots of wind. And from 10 Knots, the speed gain is clear and quasi uniform, of about 0,3 Knots. The sail reduction is slightly delayed, necessary from 14 Knots instead of 13 Knots for the version without floats.

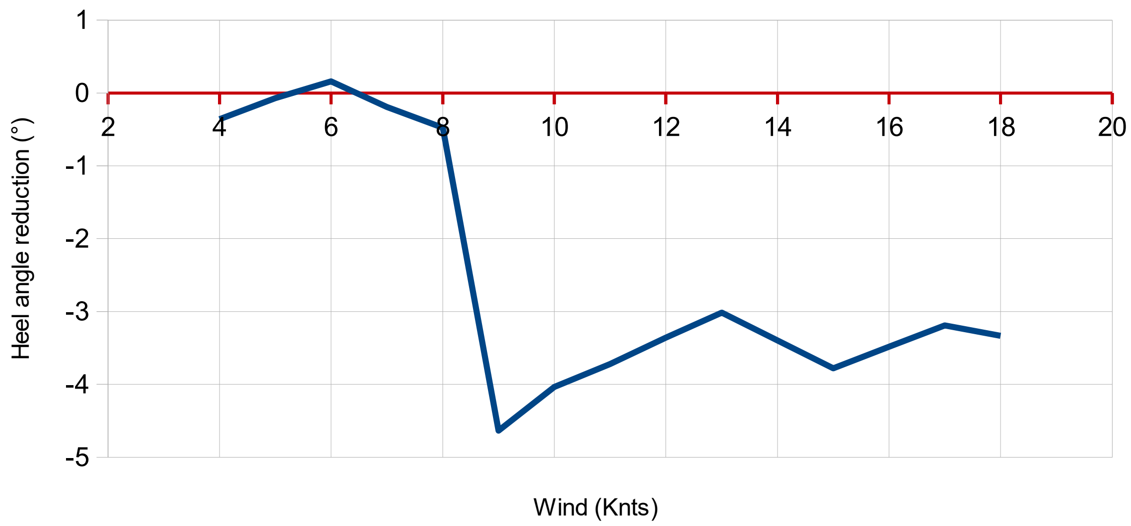


F3 boat heel angle, when upwind on calm water



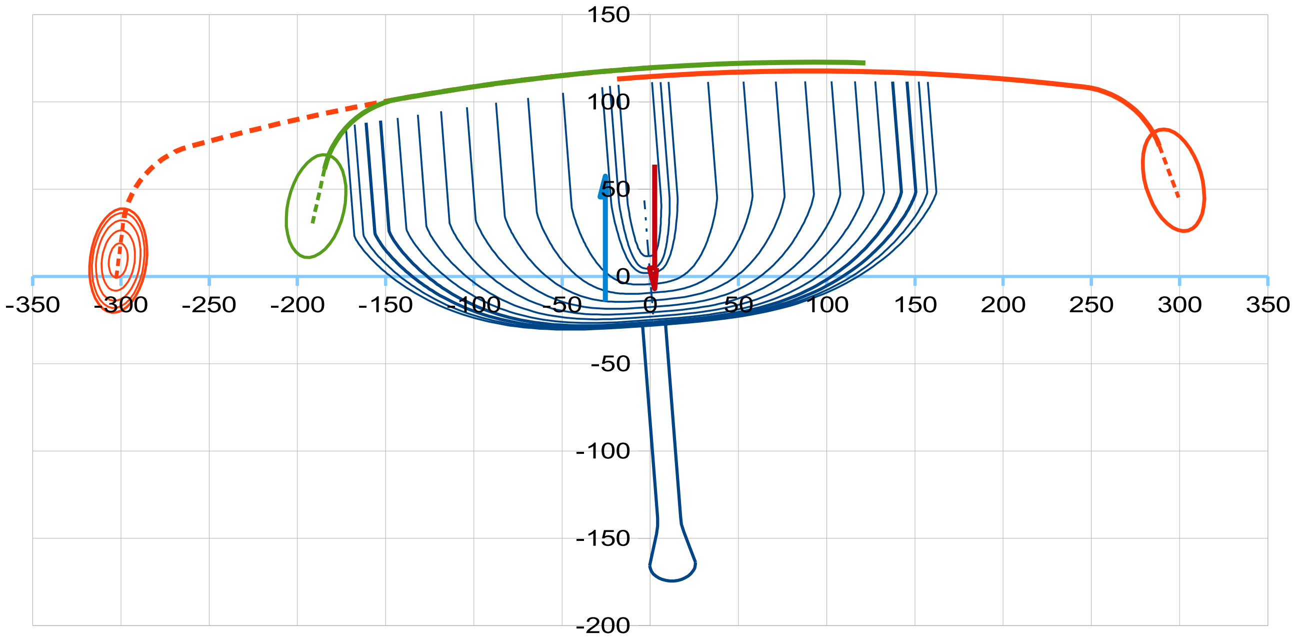
>>> As long as the leeward float is retracted (up to 8 Knots of wind), the heel is, as predictable, quasi identical to the one without floats. With the deployed float, one can obtained a -3° to -4° lower heel angle. The practical limit triggering the sail area reduction decision is heel ≤ 25° in the case without floats, and becomes ≤ 23° with floats.

Heel angle reduction when upwind, versus wind force



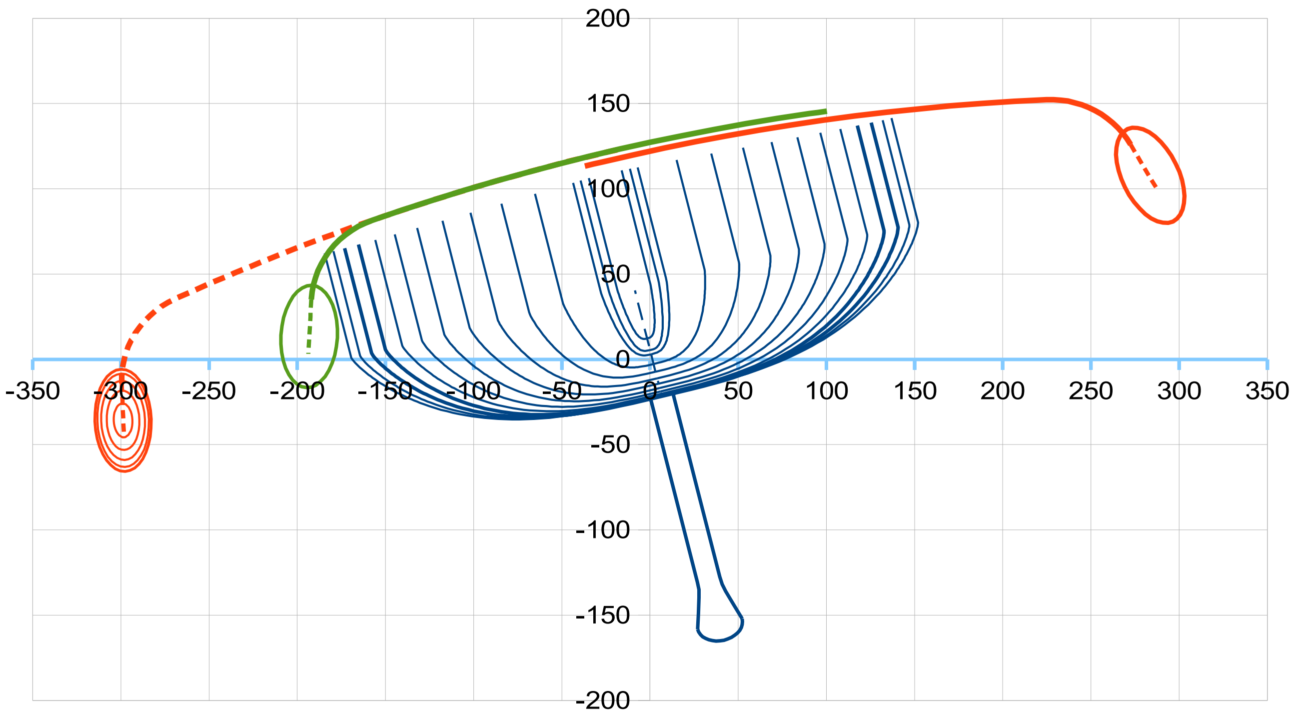
Some typical configurations, of heel and speed when upwind in function of the wind force :
(the windward float being deployed to contribute a bit to the RM)

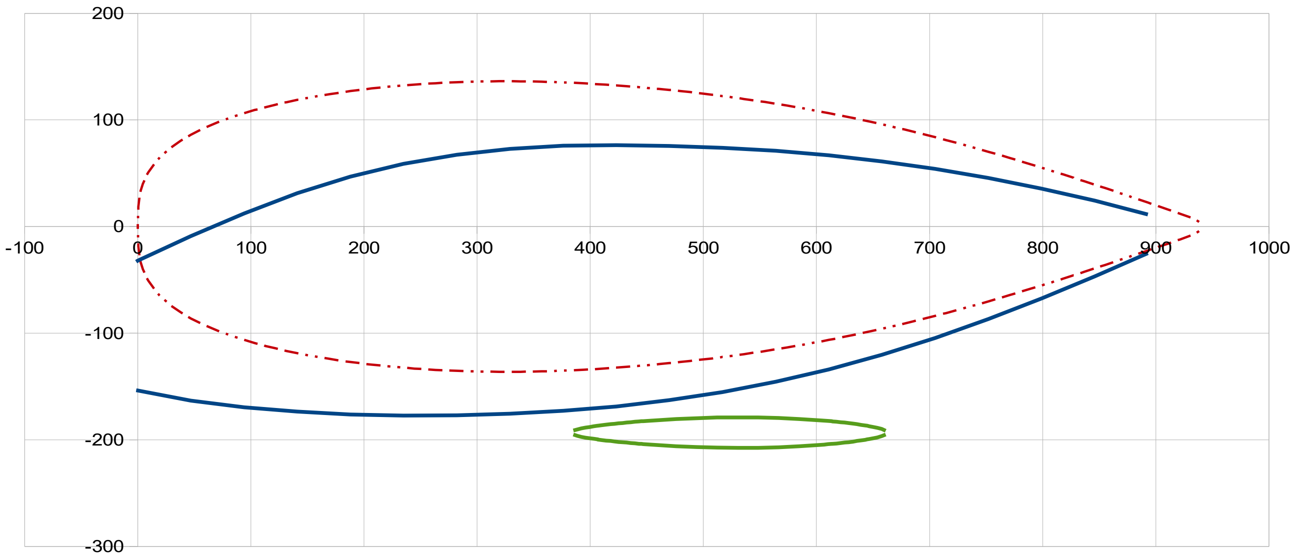
Upwind, wind 5 Knots >> **Float retracted (in green)**, Heel 4,40° **> Boat speed 4,50 Knots**



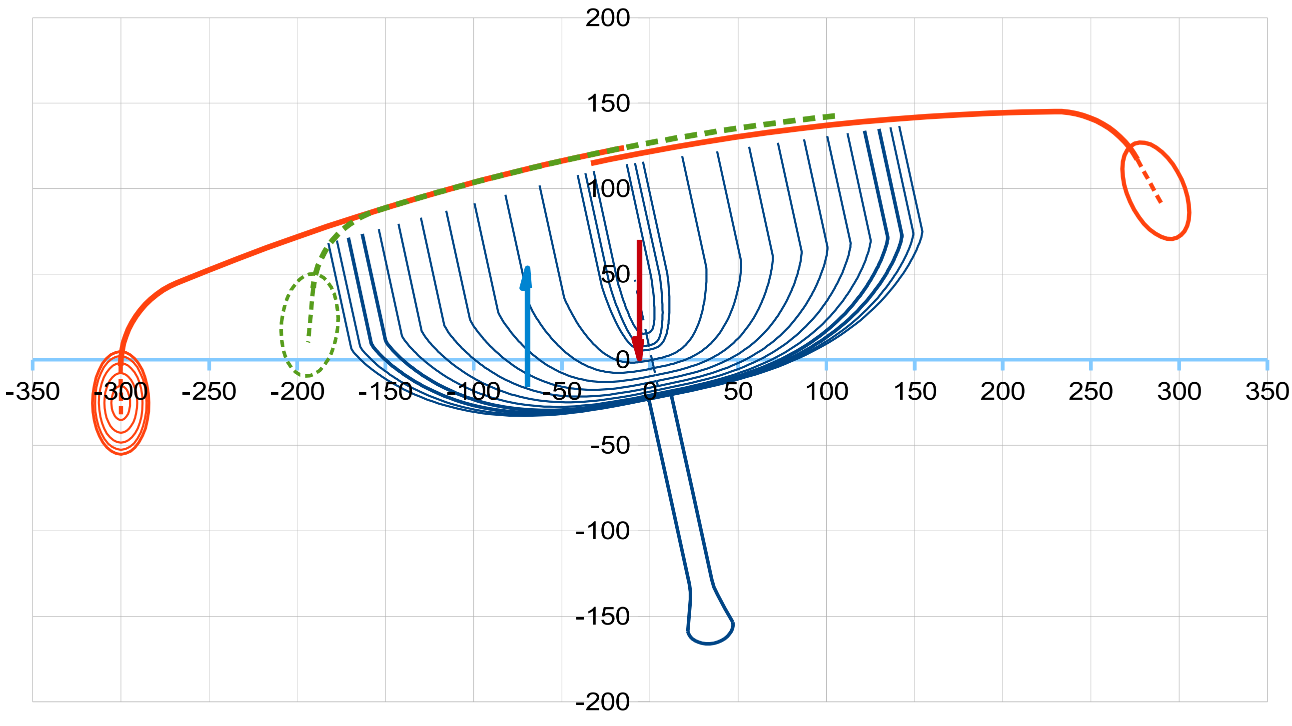
Upwind, wind 8 Knots >> it is the **limit case with float retracted (in green)** which then finds itself slightly in contact with water of 17cm, so an immersed volume of 63 liters.

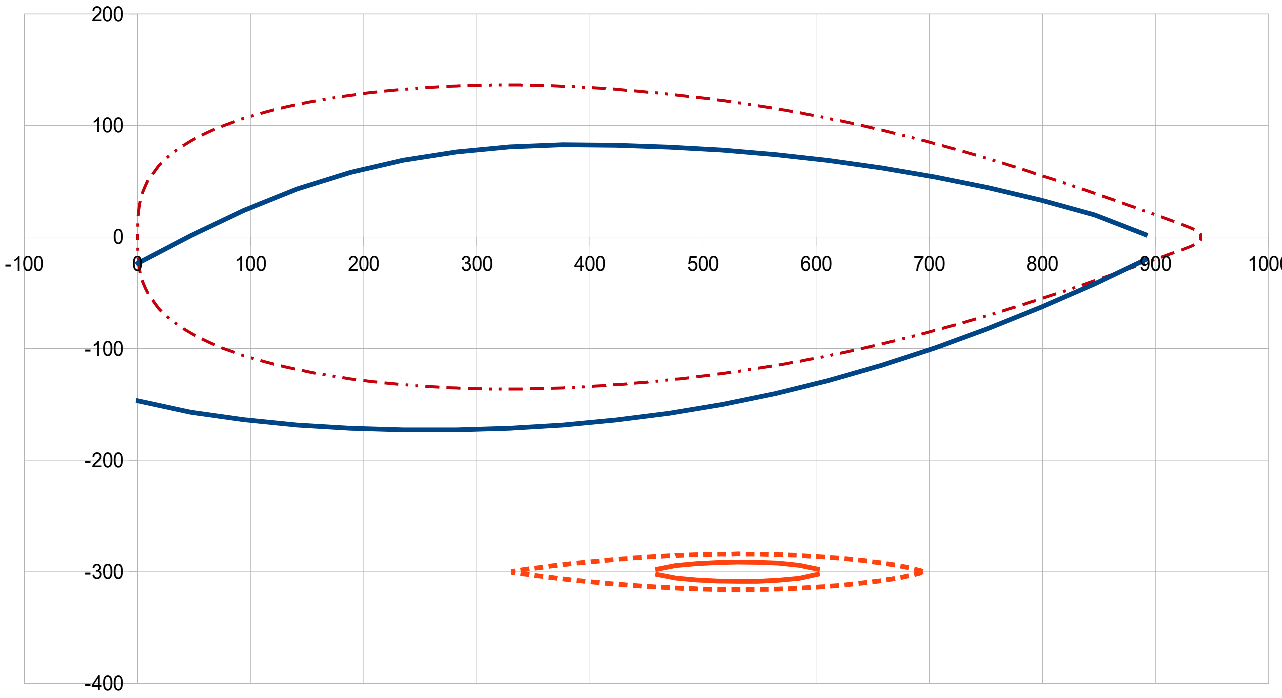
>>> Heel 13,86° Boat speed **5,80 Knots,** a bit lower than the one without floats (5,85 Knots)



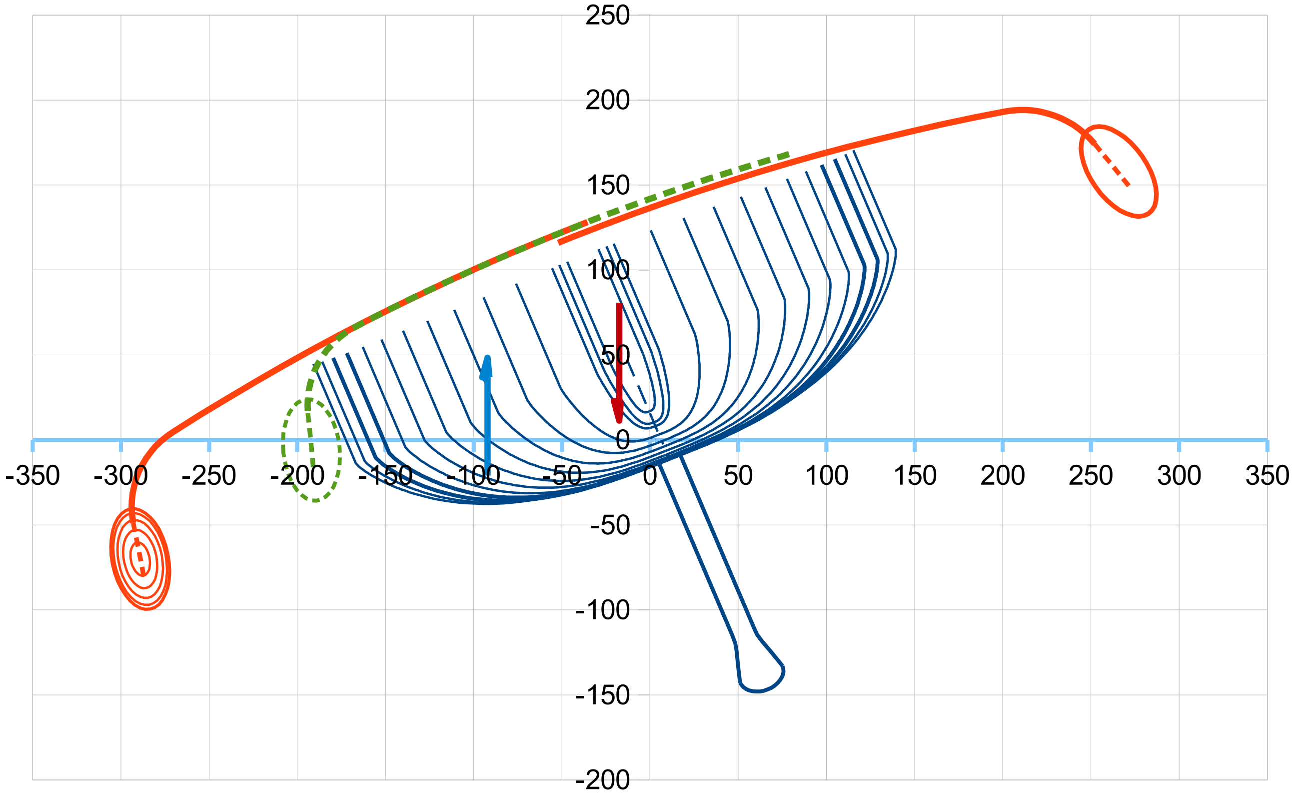


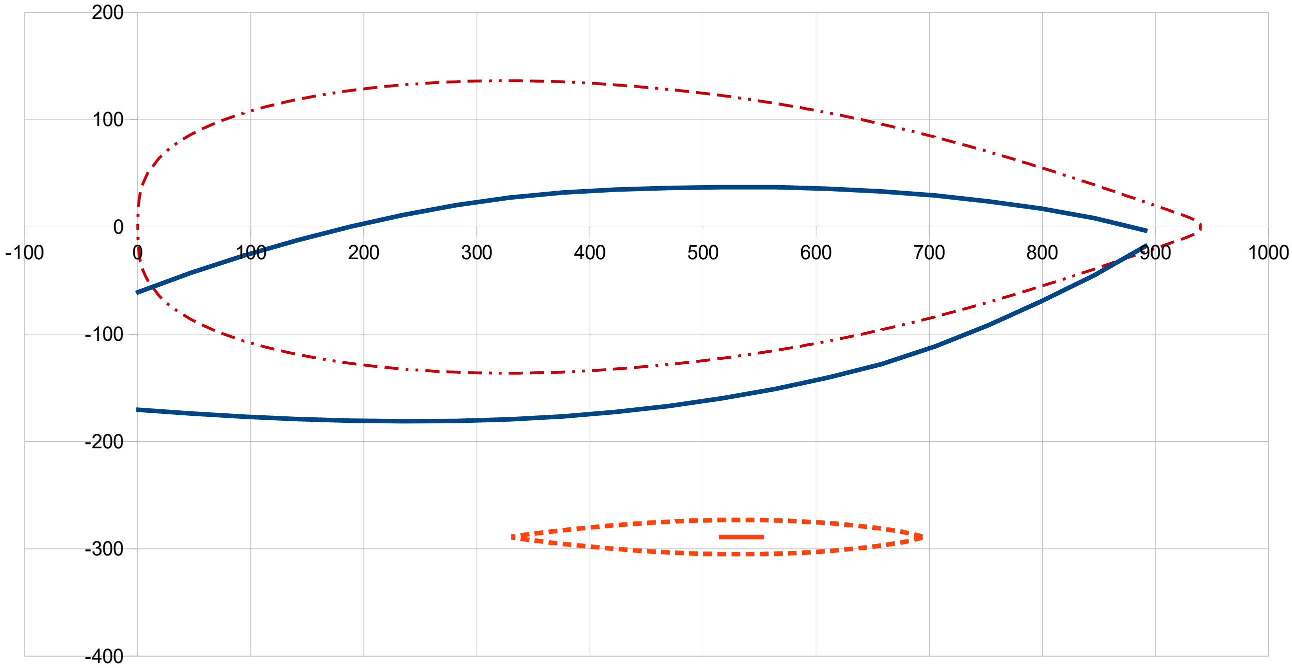
Upwind, wind 9 Knots >> **Float deployed (in red)**, Heel 11,94° > Boat speed **6,11 Knots**
>> it becomes profitable to deploy the float from 9 Knots of wind, it is then quasi fully immersed, and the speed reached is 6,11 Knots, a bit over the one without floats (6,01 Knots) with a lower heel (11,94° / 16,58°)





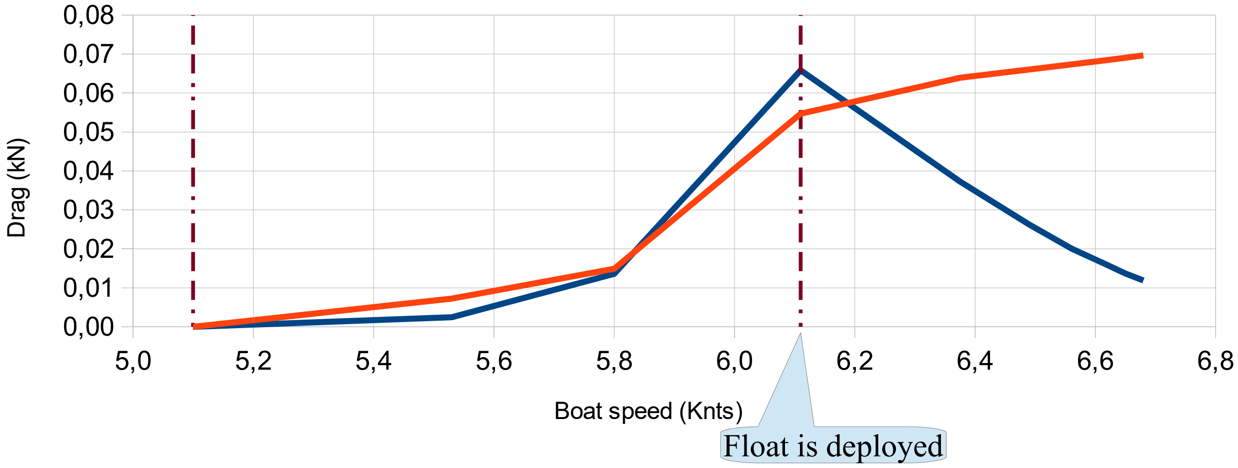
Upwind, wind 14 Knots >> Float deployed (in red), Heel 22,35° > Boat speed **6,65 Knots**
In such conditions, the version without floats ends up in an extreme heel 29,4° at the speed of 6,33 Knots. To note the immersion of a portion of the support arm (« aka ») of ~ 50 cm : the corresponding drag is taken into account, but not the eventual dynamic lift.



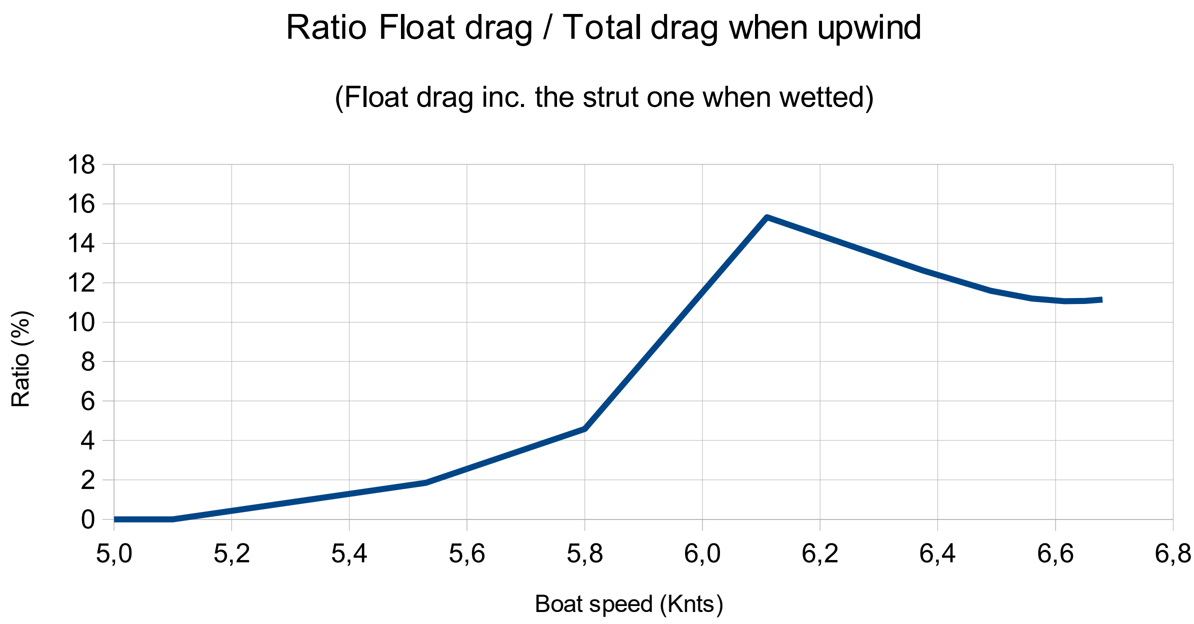


Float drag components when upwind
(output of the VPP)

Blue : wave drag Red : friction drag

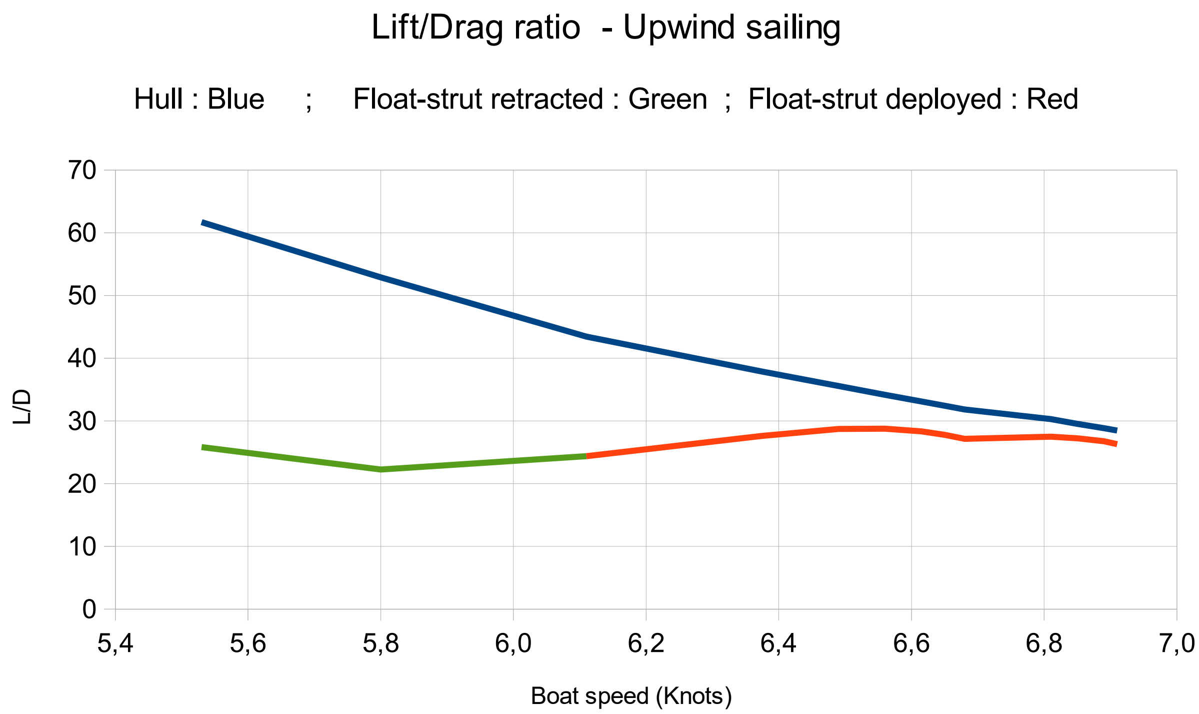


>>> When the float is retracted and not or few immersed (Boat speed < 6 Knots) or deployed and quasi fully immersed (Boat speed 6,11 Knots), the two drag components are of same order of magnitude. Then, the float immersion increases with the heel, the boat speed continue to increase (up to 6,68 Knots), and the wave drag rapidly falls in comparison with the friction drag.



>>> in %, the float drag reaches a peak of about 15% of the total drag at around 6,1 Knots, then decreases toward 11% at the max speed 6,6 - 6,7 knots.

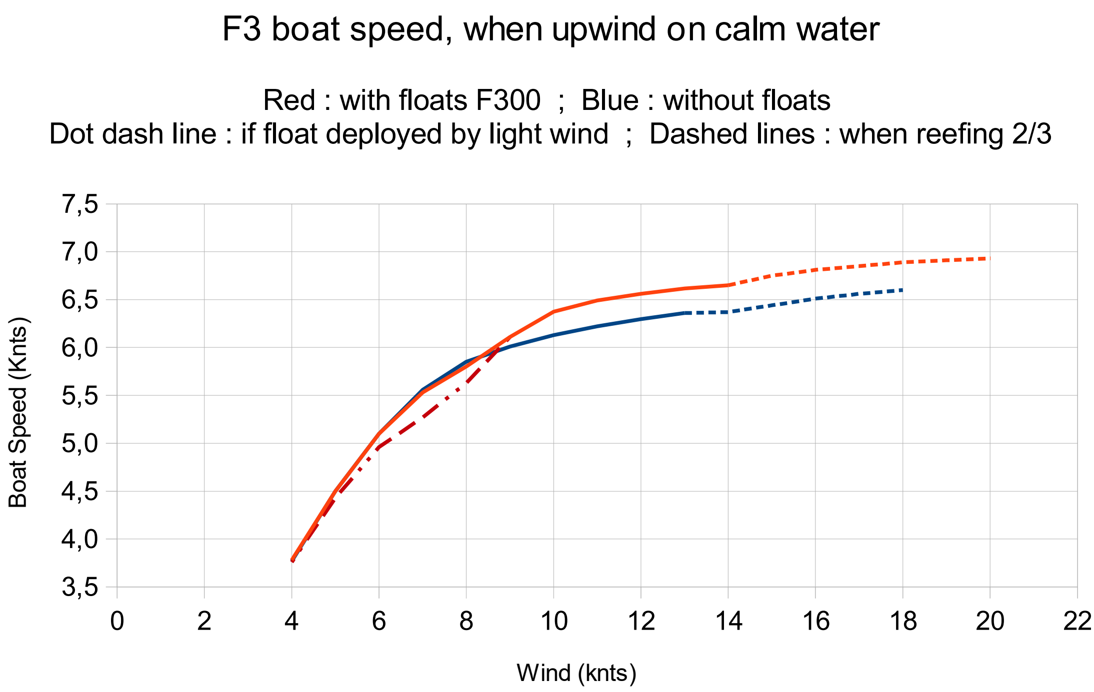
In complement, it is also instructive to compare the Lift/Drag ratios of the float and of the central hull, the lift here being exclusively of archimedian type which does not detract from the relevance of the comparison.



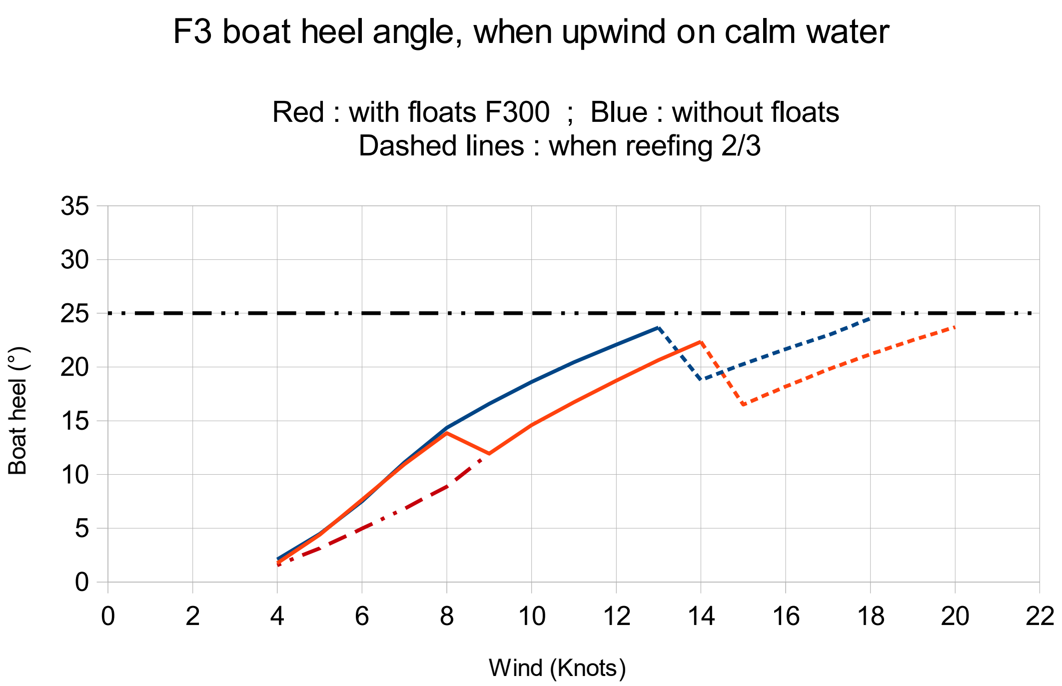
>>> the L/D ratio of the float remains lower than that the one of the hull, despite that the float can be advantageous thanks to its significant contribution to the righting moment RM.

What could be the speed if the leeward float is permanently deployed even by light winds ≤ 8 Knots ?

>>> here are the speed and heel in that case curves (in dot-dashed line) :



>>> That generates a loss of speed in the range 6-8 Knots of wind, of about 0,3 Knots at max with regard the version without floats.



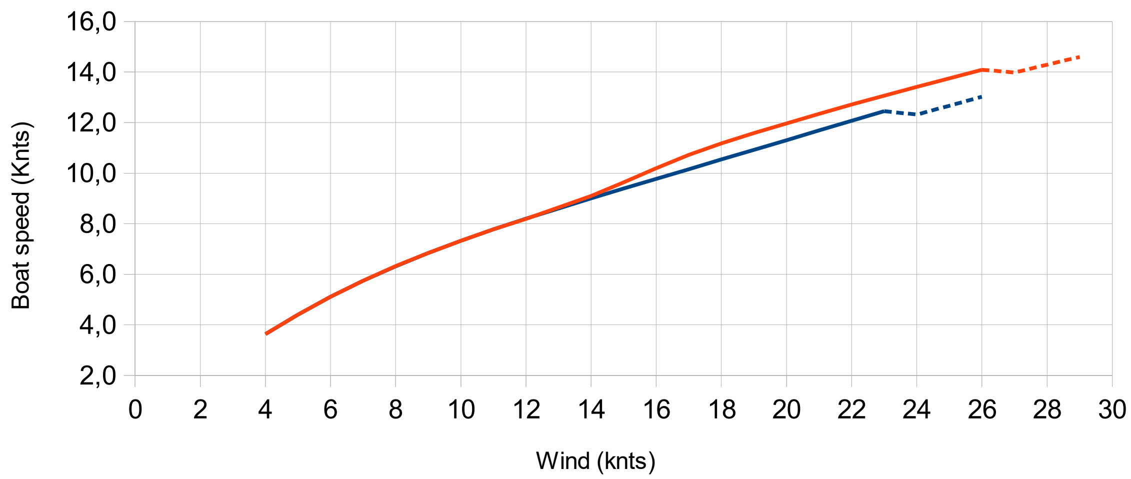
>>> the heel is then of course reduced, maintained at 10° instead of 14° when 8 Knots of wind, this is an advantage that can be sought in cruise mode at the cost of a slight speed deficit.

5. Comparison when downwind (twa 140°)

As for upwind, we consider two operating modes : leeward float retracted or deployed. In the case of a downwind sailing at twa 140° , the retracted mode can be maintained and the most profitable up to 12 knots of wind, and then the deployed mode becomes regularly better from 13 knots without causing discontinuity in the speed progression.

F3 boat speed downwind (twa 140°)

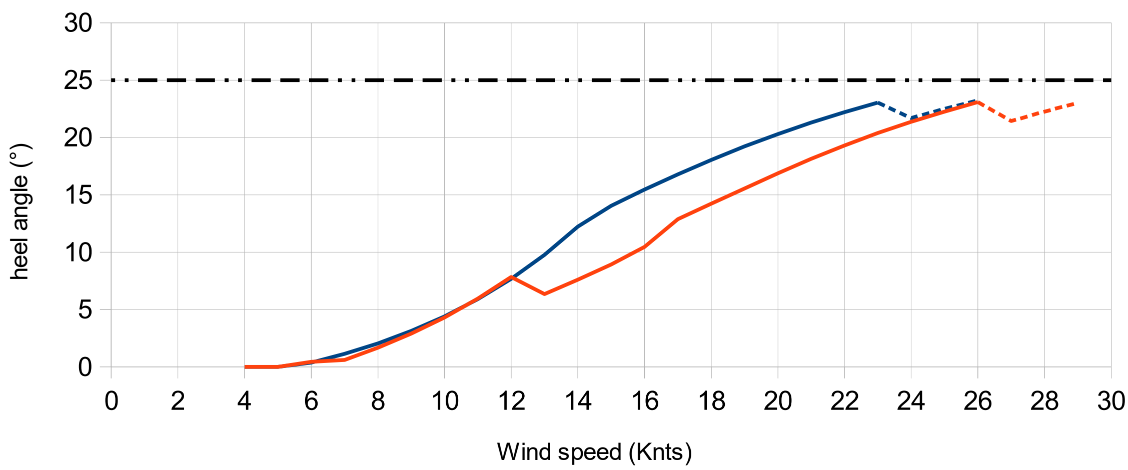
Red : with floats F300 ; Blue : without floats
Dashed lines : when reefing 0,8



>>> The transition between the retracted float and the deployed float modes is between 12 and 13 knots of wind. And from 13 Knots, the gain in speed progresses regularly up to + 0.65 Knots, and even a little more when the wind is > 23 Knots because the version without floats must then reduce its sail area earlier.

F3 boat heel angle downwind (twa 140°)

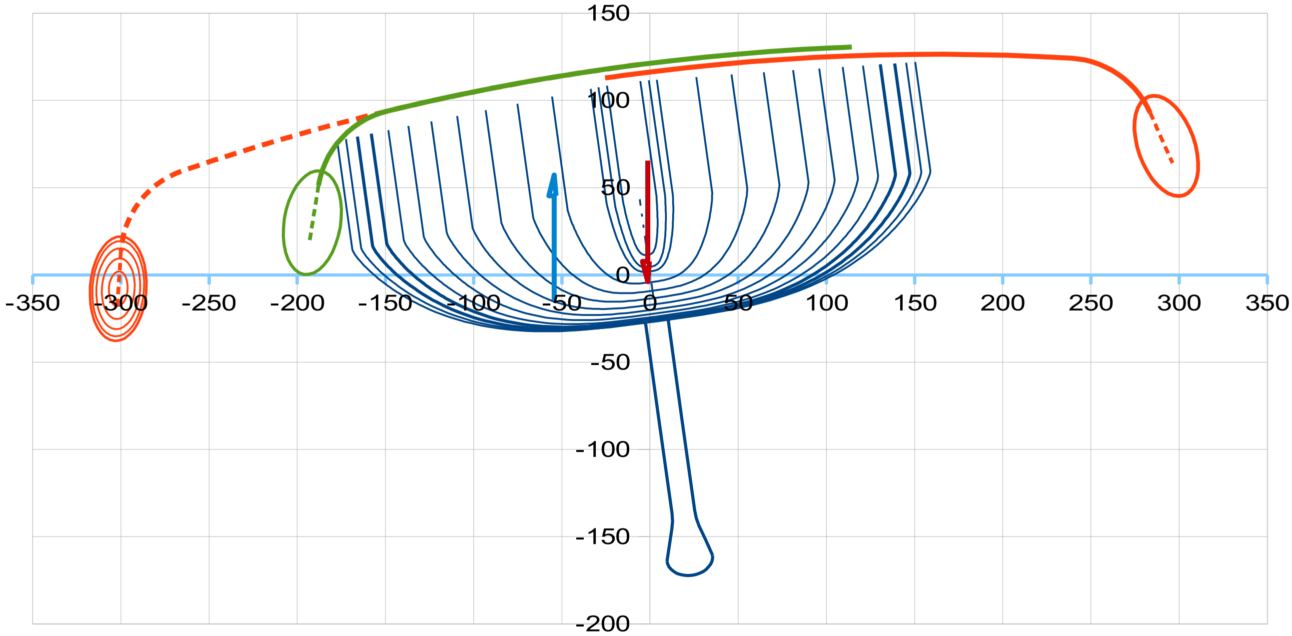
Red : with floats F300 ; Blue : without floats
Dashed lines : when reefing 0,8



>>> As long as the leeward float is retracted (up to 12 knots of wind), the heel is almost identical as with the version without floats, the float itself is not in contact with the water because the heel remains small (< 8 °). With the float deployed, we obtain a smaller heel of 3° to 5° and can keep its nominal sails surface up to 26 Knots.

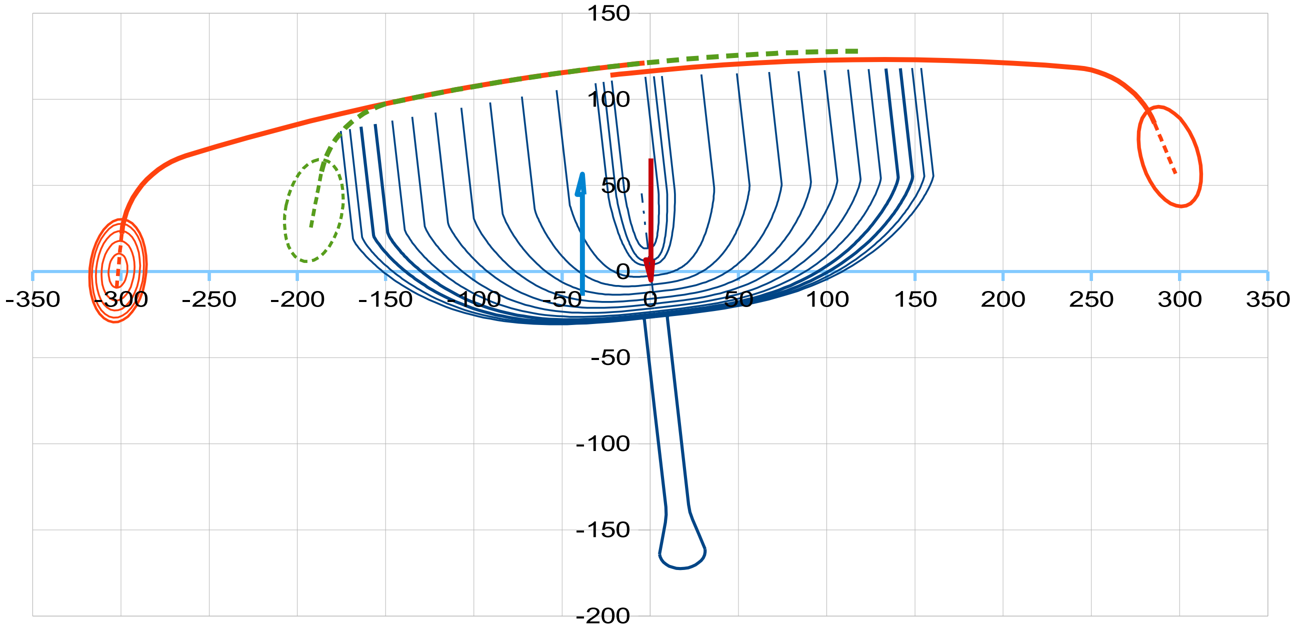
Some typical configurations, of heel and speed when downwind in function of the wind speed :
(the windward float being deployed to contribute a bit to the RM)

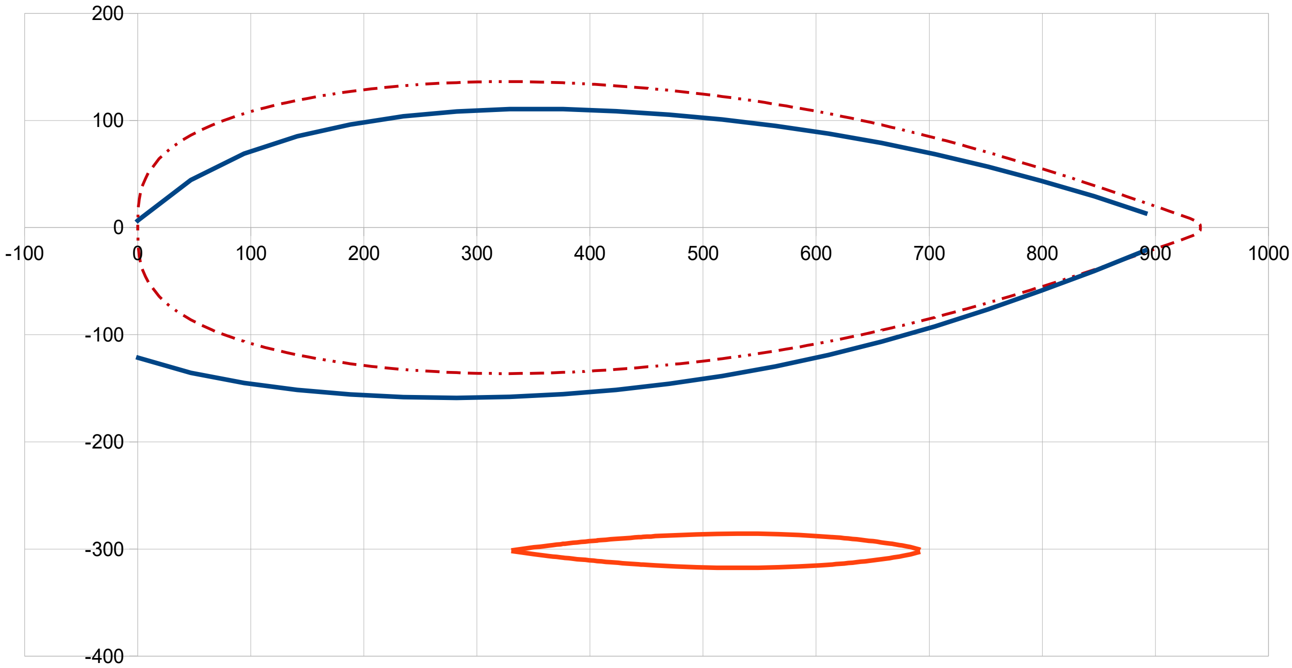
Downwind (twa 140°), wind 12 Knots >> **the retracted Float (in green) is just flush to the water**
>>> Heel 7,84° **Boat speed 8,19 Nds**



>>> before that configuration with 12 Knots of wind, the retracted float is not in contact with water.

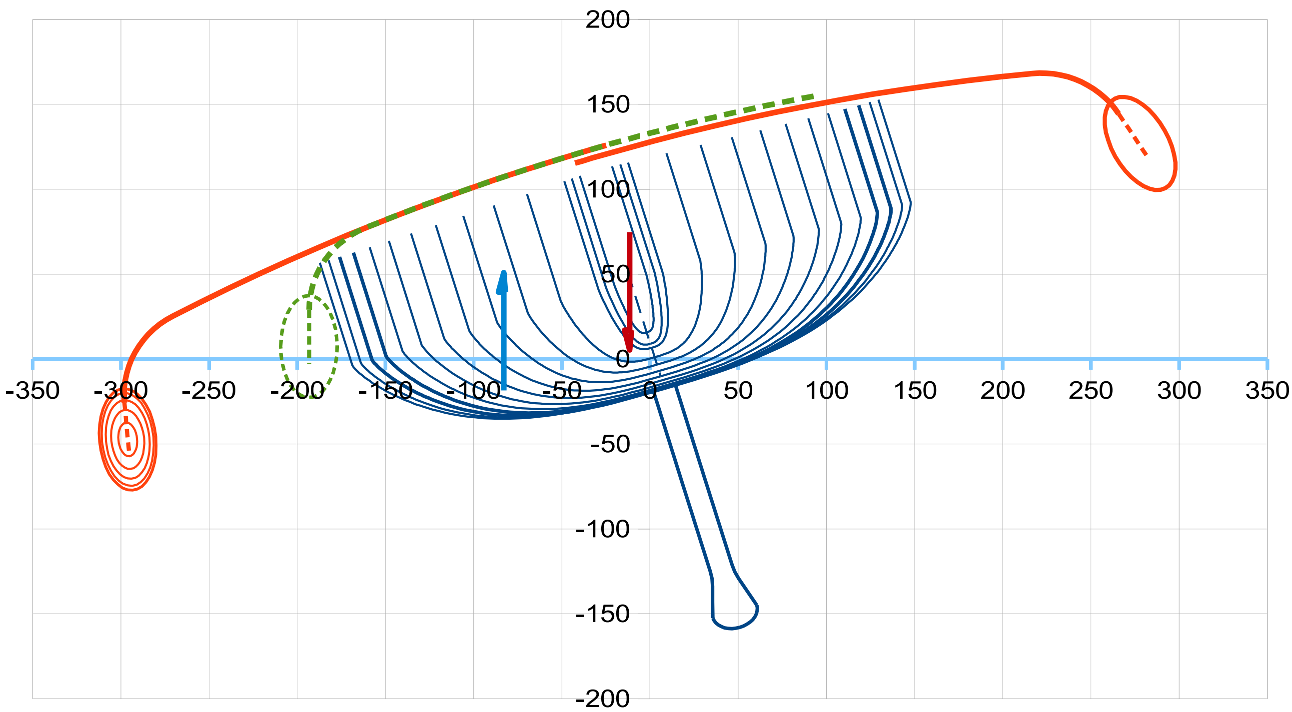
Downwind (twa 140°), wind 13 Knots >> **Float deployed (in red)** Heel 6,34° Boat speed **8,65 Kts**



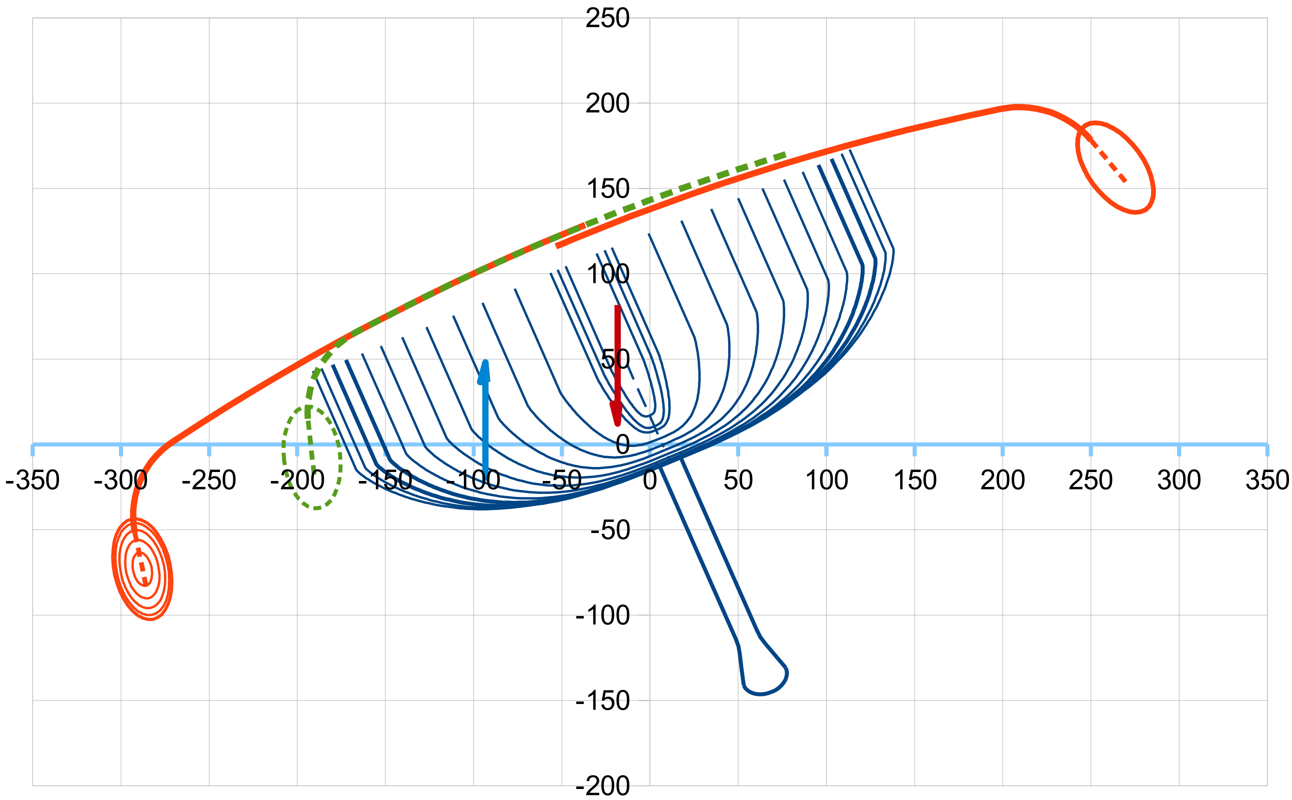


>>> the float is at mid-immersion, and at boat speed 8,65 Knots the Froude of the float is 0,75 far from the peak at 0,50 , which reduces the relative importance of its wave drag in the total (3.8%).

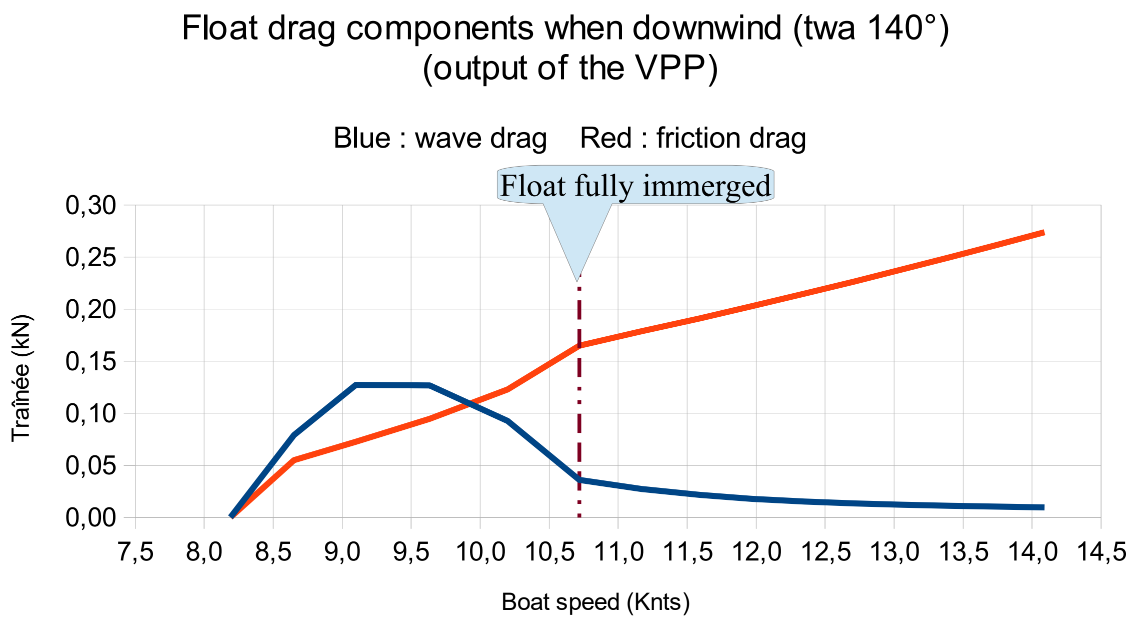
Downwind (twa 140°), wind 20 Knots >> Float deployed (in red), Heel 16,9° Boat speed **12,0 Kts**



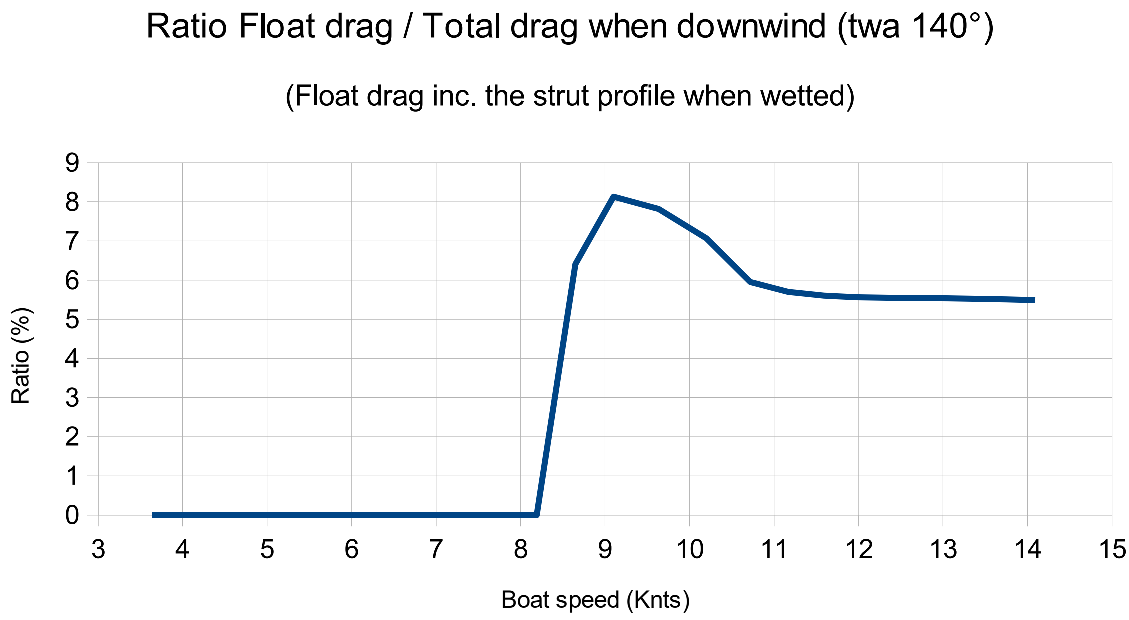
Downwind (twa 140°), wind 26 Knots >> Float deployed (in red), Heel 23,1° Boat speed **14,1 Kts**



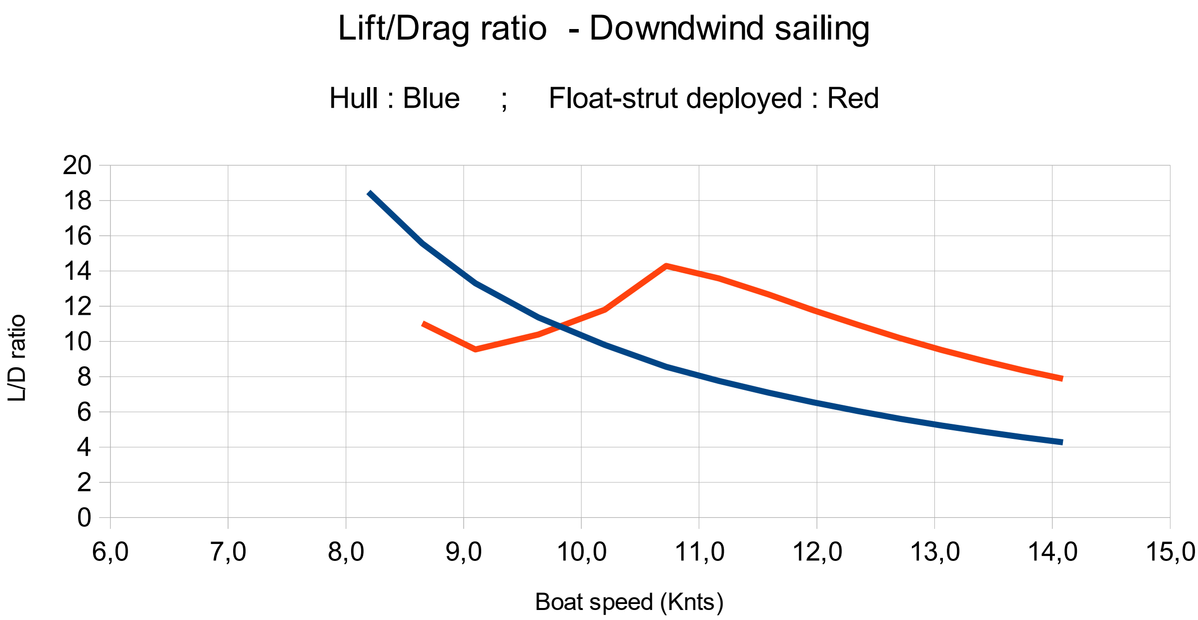
>>> ~ 23° is the heel limit before a sail area reduction



>>> the wave drag becomes negligible from a boat speed of 10 knots and especially when the float becomes completely submerged (at ~ 10,7 Knots)

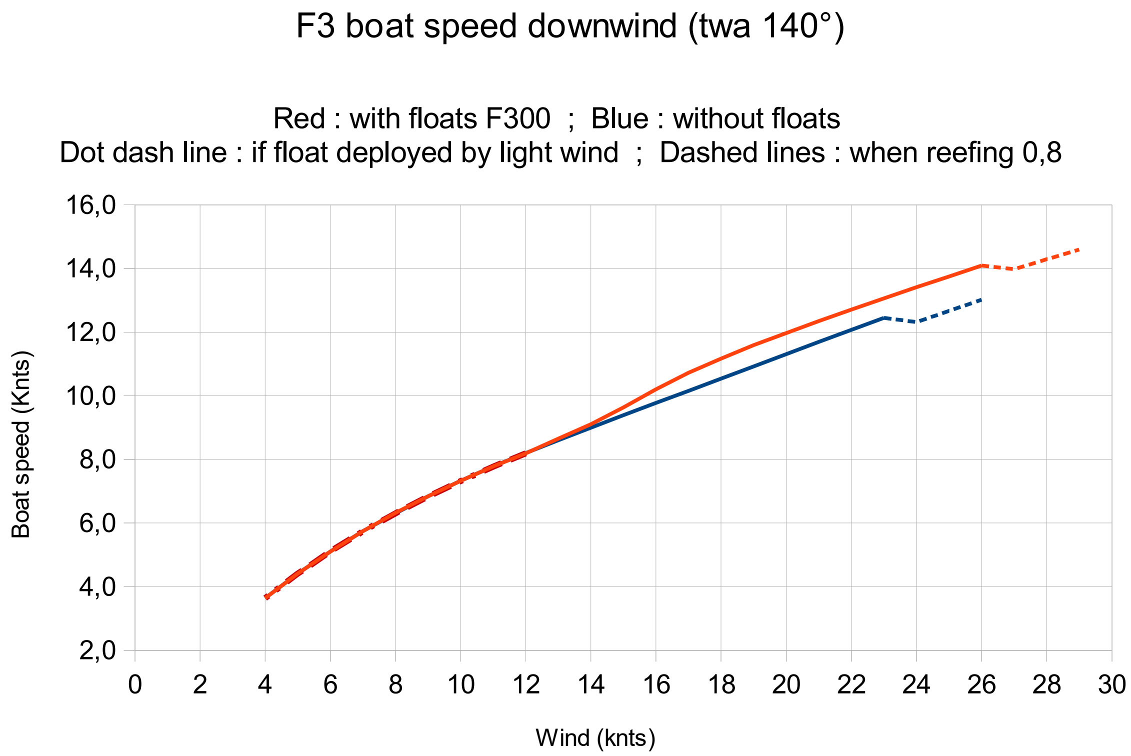


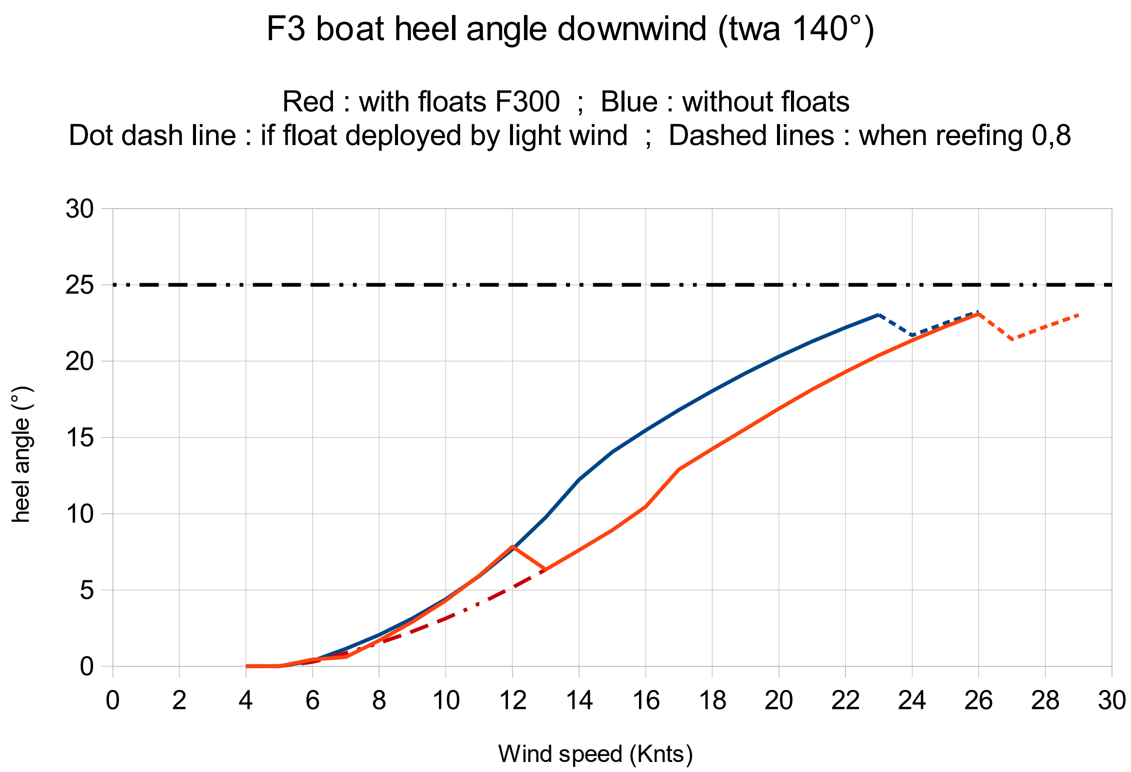
>>> Up to around 8 knots, the float can be kept in retracted mode and without contact with water. In %, the float drag reaches a peak of around 8% of the total drag towards 9 knots (when the float is deployed and at mid-immersion) then decreases and levels off at 5.5% at high speeds > 12 knots.



>>> the L/D ratio of the float system becomes better from a certain speed, around 10 knots, which can be reached downwind. So we can say that the system is then twice winning: not only does it make an important contribution to the RM, but in addition its archimedean contribution is with less drag. At 14 knots, the L/D ratio is 8, this remains honorable if we compare it to what a foil could give under these same conditions.

What would be the speed if the leeward float was in deployed mode even in light to moderate winds ≤ 12 knots? Here are the speed and heel curves with this case added through the dot-dashed line :



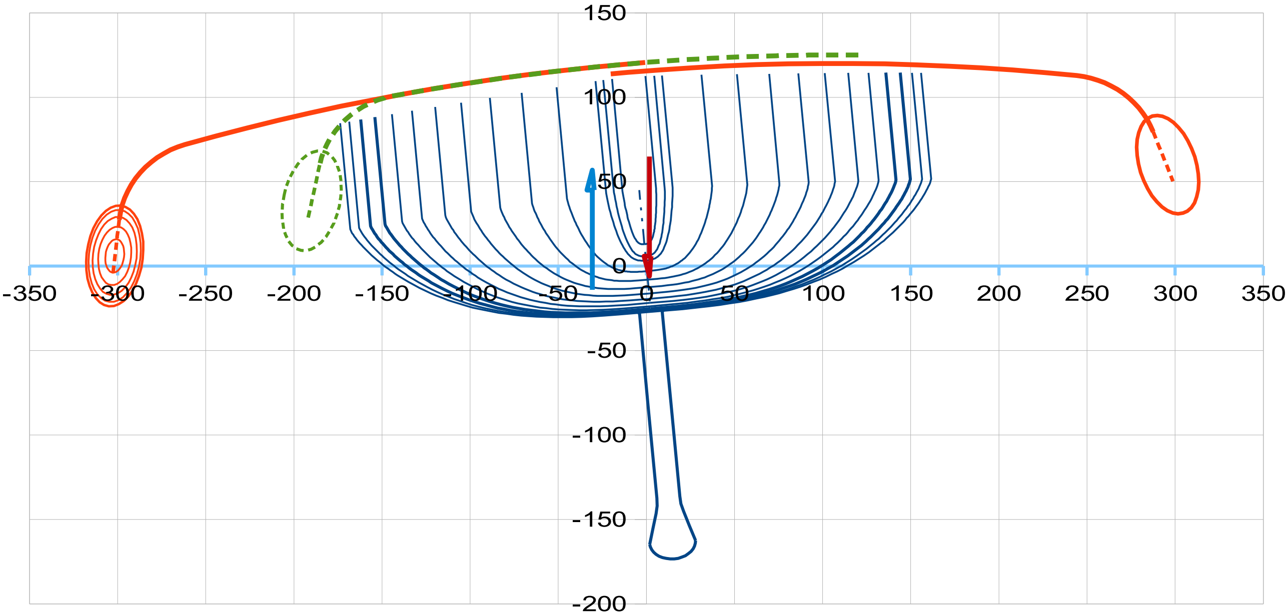


>>> unlike upwind, there is no noticeable difference in speed. That can be explained by two combined factors :

- on the one hand the heel remains low, at most 5.2 ° with 12 knots of wind, and under these conditions the float remains moderately submerged (36% in volume with 12 knots of wind), it behaves like a trimaran float.

- on the other hand the speed is significantly higher than upwind, so that the relative drag of the float is lower when compared to that of the main hull.

Configuration with 12 Knots of wind, F300 deployed >>> Heel 5,17 ° and Boat speed 8,19 Kts

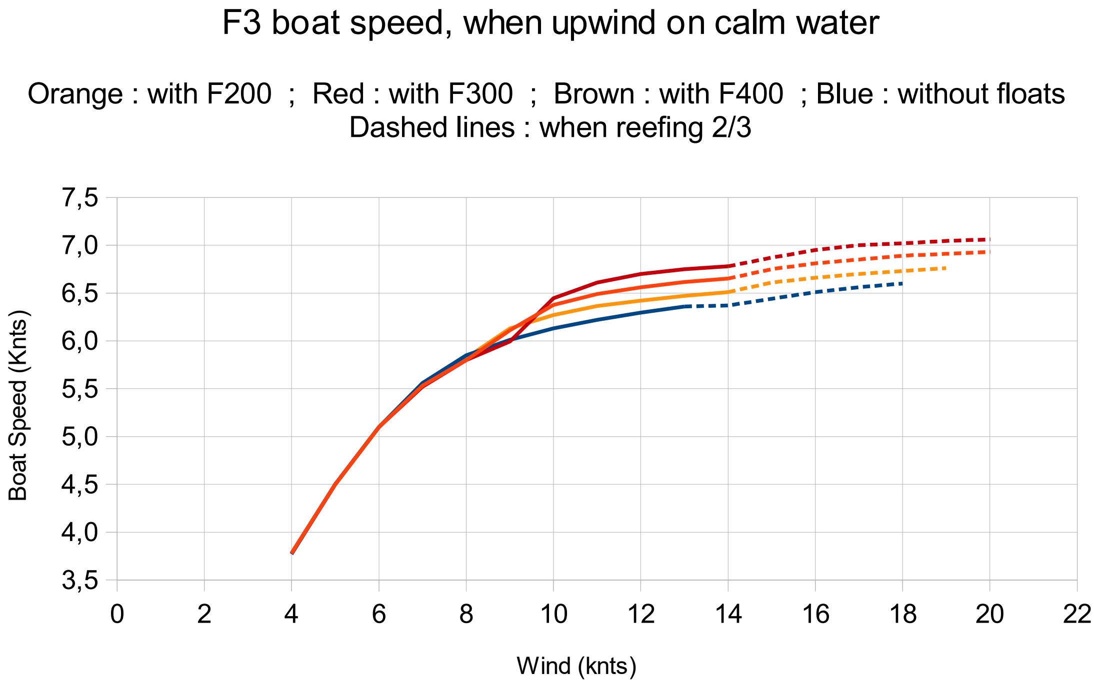


6. Float volume influence

For this study, from the F300 model (300 liters), we consider the F200 and F400 models (200 and 400 liters respectively) in geometric similarity with the F300, as well as in mass similarity with reallocation of the difference in the weight of the ballast so as to maintain a homogeneous comparison of performance at equivalent light ship weight. In detail, this leads to :

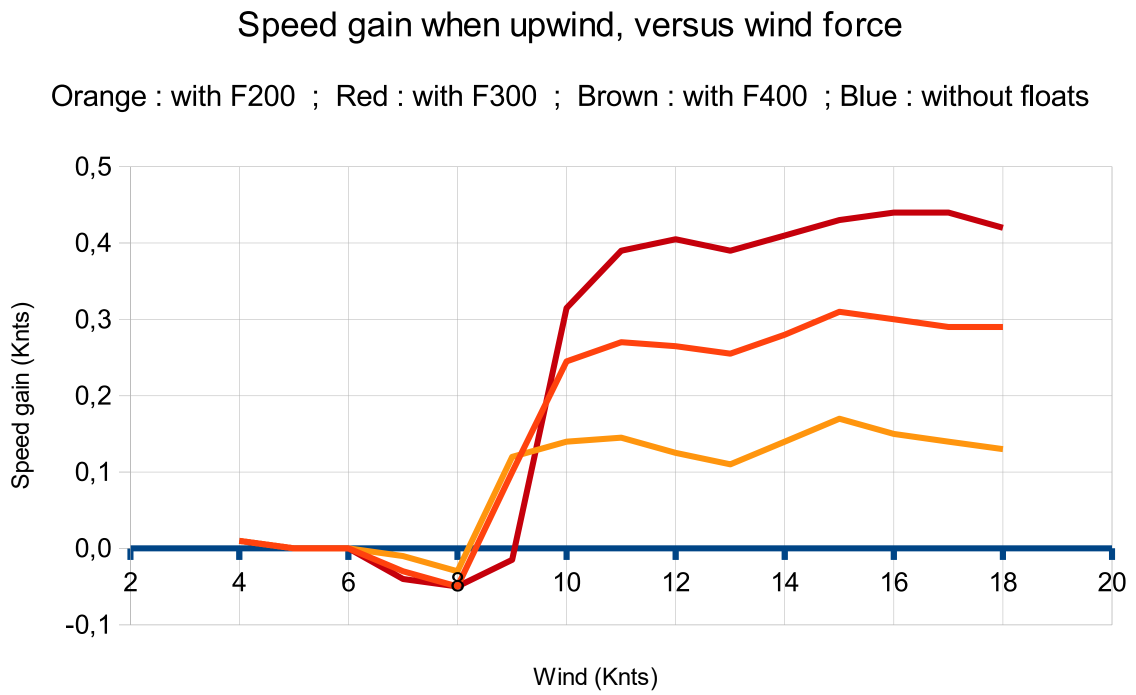
	Float F200	Float F300	Float F400	Version without floats
Elliptical max section (cm x cm)	52,41 x 27,95	60 x 32	66,04 x 35,22	
Length (cm)	317,6	363,5	400,1	
Volume (m3)	0,2010	0,3015	0,4020	
Wetted surface (m2)	2,811	3,683	4,462	
L x Ep of the support arm (mm x mm)	326,6 x 29,4	400 x 40	46,19 x 41,6	
Provision for the mass of the system (kg)	120	180	240	0
Ballast (kg)	1072	1012	952	1192
Light ship displacement (kg)	3250	3250	3250	3250

Comparison of performances when upwind :

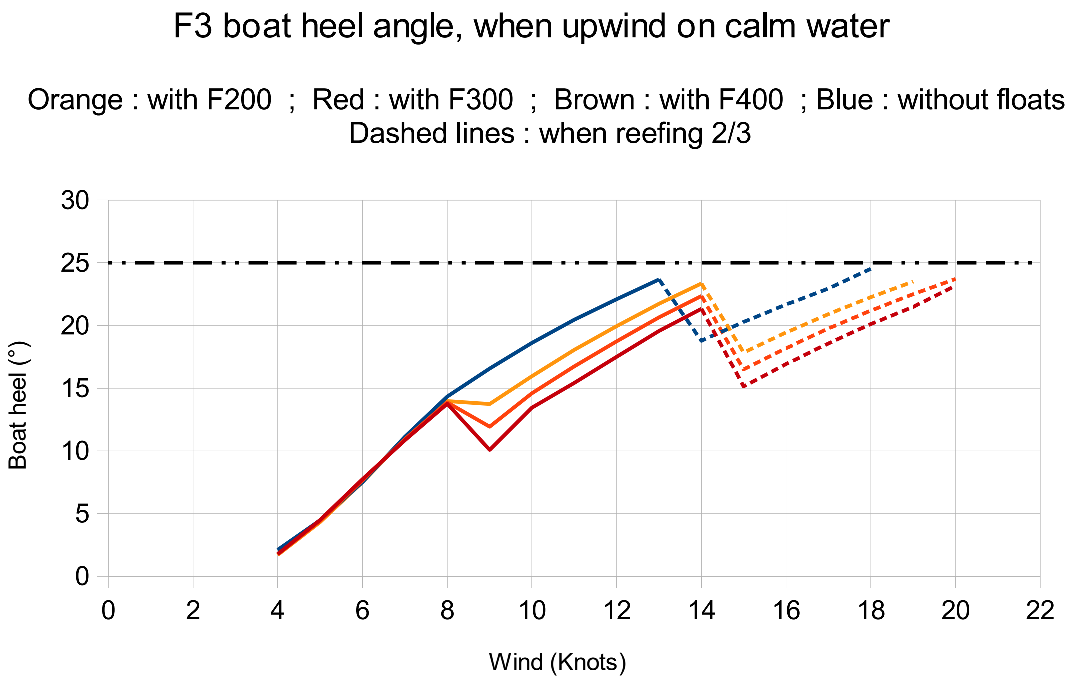


>>> the optimal transition between the retracted mode and the deployed mode is, in the 3 cases,

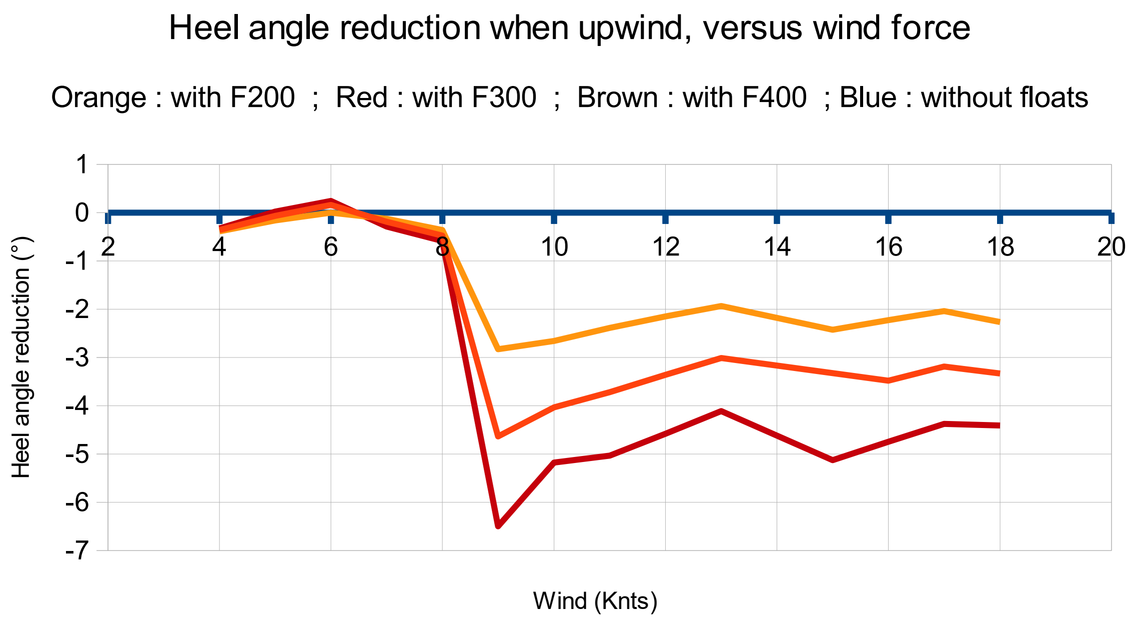
between 8 and 9 knots of wind. At 9 knots in deployed mode, the F400 gives an identical speed to the referent without floats, while the F200 and F300 are already a little faster. But from 10 knots of wind, the hierarchy of performance gain is established logically (faster with a more powerful float) with almost identical and uniform speed differences between the 3 versions, the curve of the differences are below :



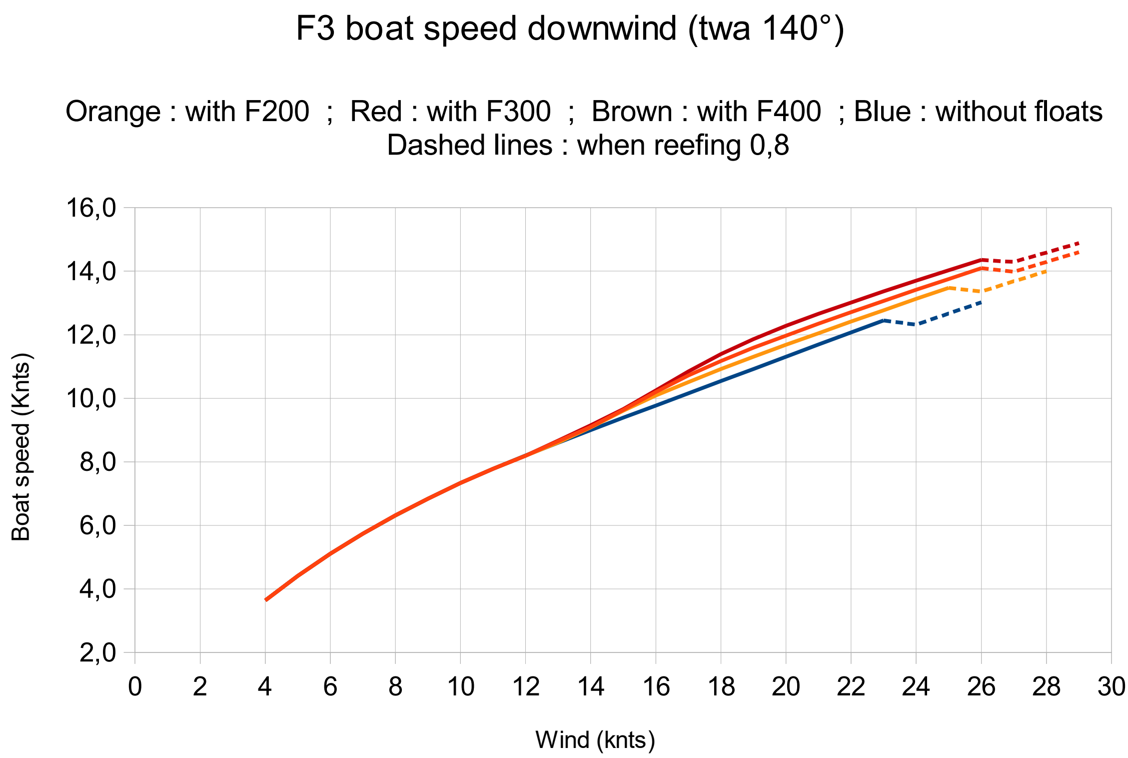
Comparison of the heels upwind :



>>> Similarly, from the deployed mode (9 knots of wind), the reduction of the heel is established logically and in almost linear relationship with the volume of the float, which can reach 5 ° with the F400, thus limiting the heel to 20- 22 ° in practice for this version.

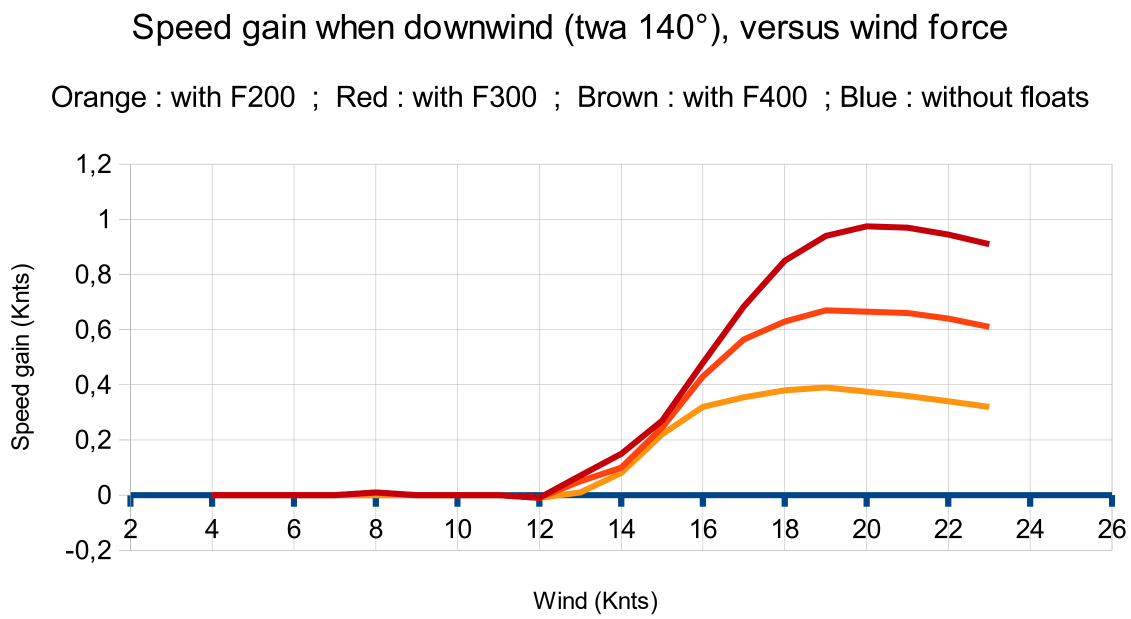


Comparison of performances when downwind (at twa 140°)

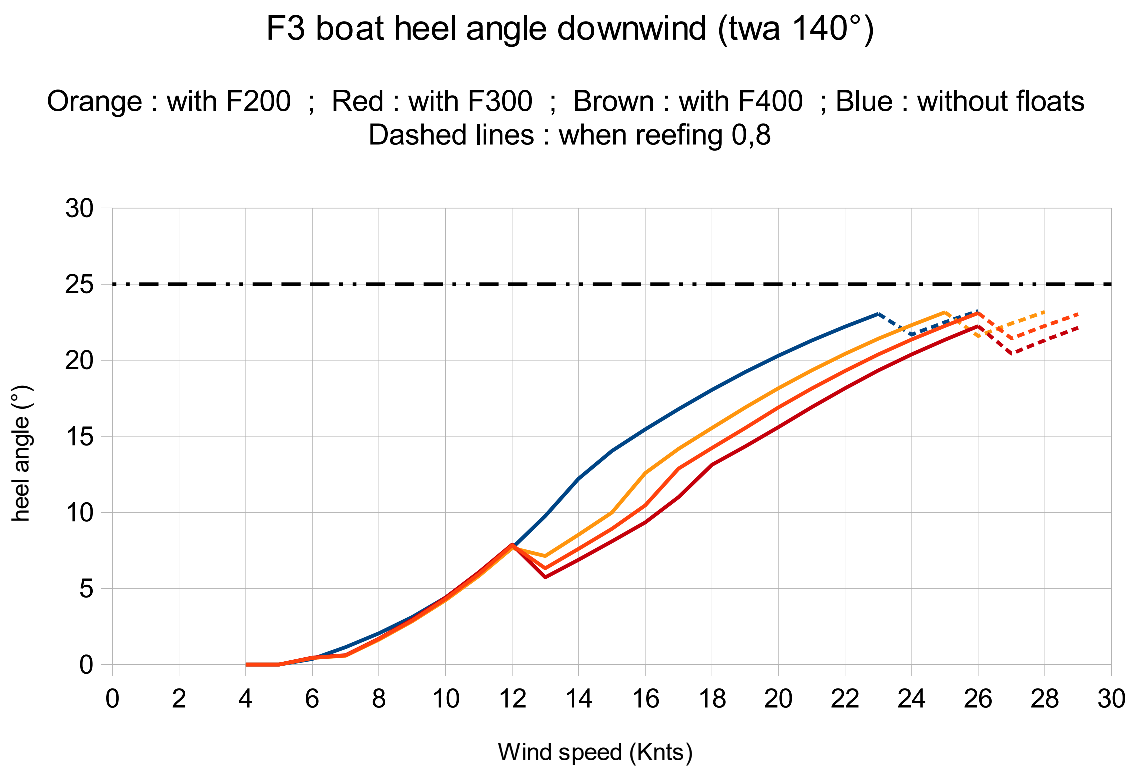


>>> the optimal transition between retracted mode and deployed mode is in the 3 cases between 12 and 13 knots of wind. Below this, the boat speed is identical because the float is not in contact with water. From 13 knots of wind, a gain in speed is gradually established with almost identical

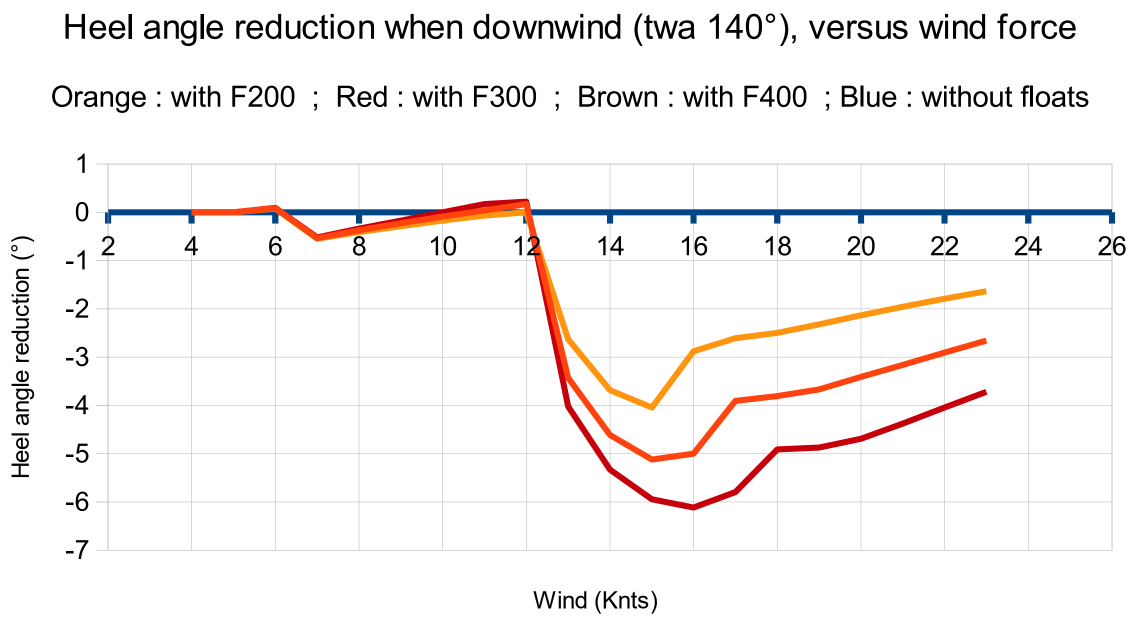
speed differences between the 3 versions. The more powerful F400 allowing to exceed 14 knots (with 25 knots of wind), meaning a gain of up to 1 knot.



Comparison of the heels downwind :



>>> Similarly, from the deployed mode (13 Knots of wind), the reduction of the heel is established logically and in almost linear relationship with the volume of the float, which can reach from -4 ° to -6 ° with the F400, according to curve deviations below:



7. From the exploratory study to the design

The purpose of this exploratory study is to demonstrate the validity of the concept thanks in particular to the two modes of use of the floats (retracted or deployed), to identify and quantify the advantages in terms of speed gain and heel reduction (upwind and downwind twa 140 °). It is not yet a finalized design, in particular as regards the system of the floats, their resistance, their rigidity : only its overall mass is provisioned (180 kg for the F300, 240 kg for the F400) assuming in particular:

- support arms (aka) of length 3,5 m, of profile type Naca chord 400 mm x thickness 36 mm (for the F300), in monolithic carbon fiber – epoxy
- floats of 100 kg/m3 globally,

The design phase should include a calculation of bending-torsion of the arm which supposes a finer estimation of the forces on the float : possible fraction of dynamic lift (should we fear a negative lift ?, I put a slight trim of + 2 ° for the float but this is only a priori), position of the center of pressure, which Munk moment to take into account ? This design phase could lead to a further optimization of the float shape beyond the exploratory approach of paragraph 2. just guided by mitigating the wave drag without excessively increasing the friction drag.

The exploratory comparison is based on versions with identical light weight ship, the differences in mass being injected in the form of ballast into the keel-bulb of the version without floats used as a reference to compare speeds and heels. This is not a comparison at equal cost, the design phase will also have to establish a first cost estimate of the float system which may be attractive in terms of the expected benefits.

8. Conclusion

This exploratory study made it possible to identify and quantify the advantages and some disadvantages or at least uncertainties of this proposal :

- **Advantages :**
  - a significant reduction of the heel, from 4 ° to 6 ° with the 400 liter float (F400), i.e. a maximum heel of around 20-22° , before thinking of reducing sail for the first reef,
  - a higher speed : ~ + 0,4 Knots from wind force 3 upwind, + 0,5 to 1,0 Knots from wind force 4 downwind (with the F400),
  - by light winds, it is possible to sail with the leeward float retracted with little or no contact with the sea surface,
  - in a marina, floats retracted, the overall width remains that of a beamy monohull, in the case studied Boa 4.07 m for a Loa of 9.75 m. The floats are then clearly above the water and not affected by the bio-fouling which develops while not sailing for a long time,
  - in case of dangerous wind / sea, it is always possible to sail with retracted floats so to not expose them to significant efforts.
  - The sliding structure, common to the two floats, is situated on the deck, in front of the mast: it does not have to be watertight it simply has to be strong and simple and can be kept open for an easy access to the mechanisms. The volume under deck is not reduced by the system. The risk of water ingress through this sliding structure is null due to the absence of any communication with the interior of the boat.

Disadvantages / Uncertainties :

- we cannot avoid a slight speed deficit when close-hauled at around 8 knots of wind speed, of the order of ~ 0.1 knots, when in the transition between the retracted / and deployed modes,
- the flexural / torsional strength of the support arm, have to be checked,
- the comparison is made at equal boat weight, the mass of the float system (180 Kg for the F300, 240 kg for the F400) being added to the mass of the bulb-keel in the version without floats. It is not an economic comparison which should compare the two versions at equal cost price (only a manufacturer can make this comparison), i.e. the version without floats could be a little longer and / or wider at equal budget. But that would only affect the gain in performance and habitability, not the heel angle reduction.

  * 180 kg being distributed in : 2 x (float 300l / 30 kg + arm type profile Naca in monolithic carbon fiber 40 cm x 3,6 cm x 3,50 m ~ 45 kg) + common drawer 30 kg

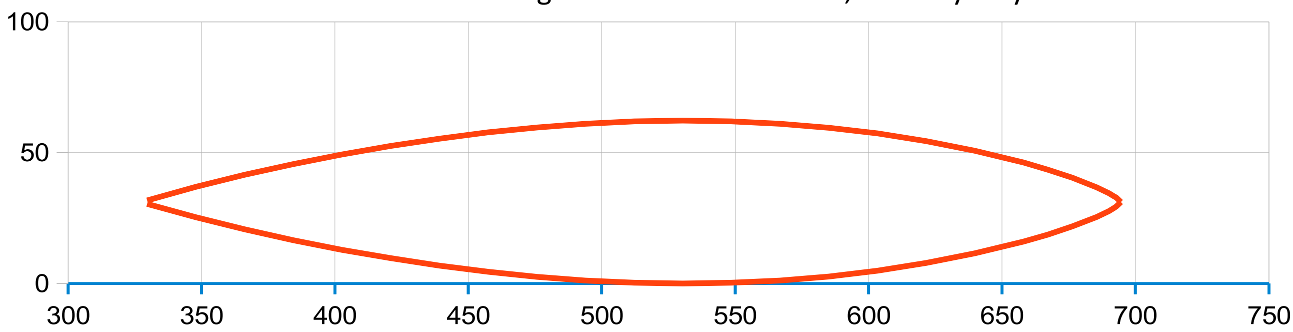
Annex A1 – drag components estimation of a streamlined 3D body

In this document, the wave drag and the friction drag components are calculated according to the immersion Z of the float for a given speed.

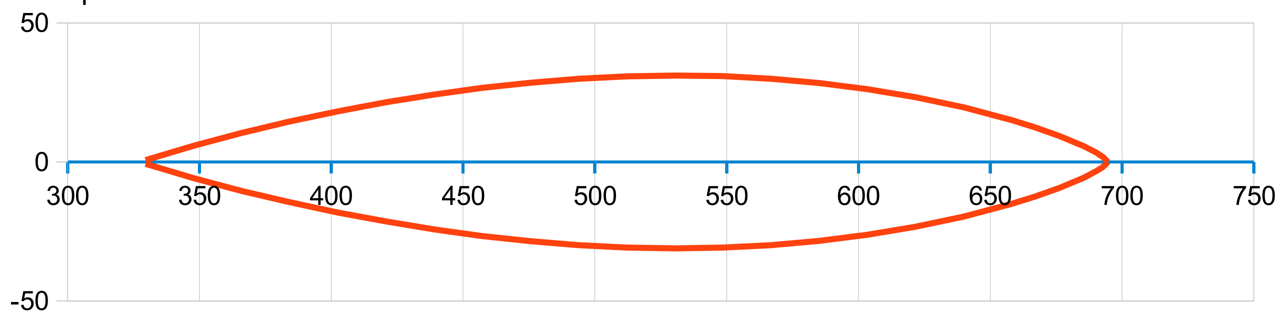
1) immersion Z : I use its relative value, i.e. the fraction of the maximum height of the elliptical section of the float, following :

Z = 0 : zero immersion, the bottom of the float is at the level of the water surface
Z = 0.5 : half-immersion, the axis of the float is the water line
Z = 1.0 : full immersion, the top of the float is at the level of the water surface
Z> 1 : deeper immersion of the float

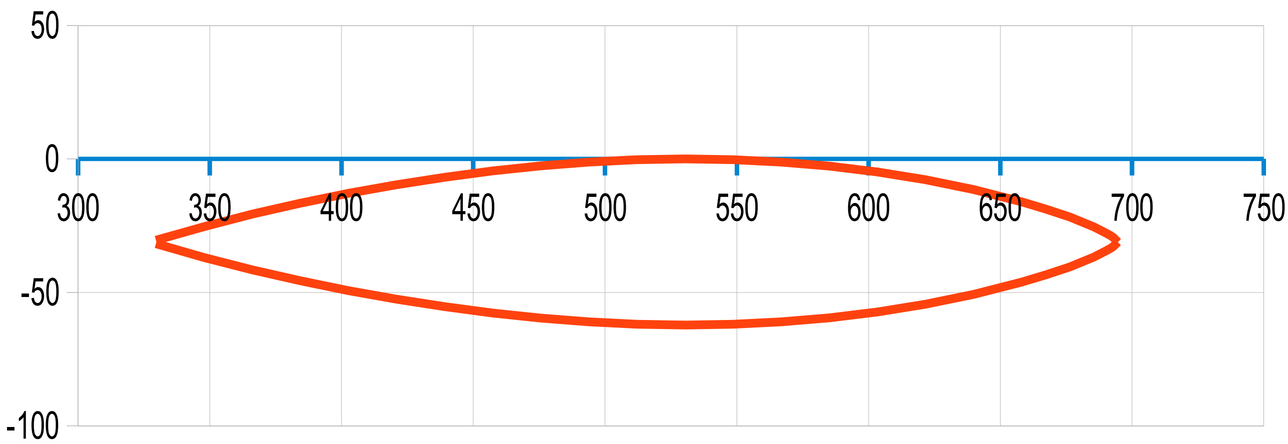
Z immersion = 0 >>> the float is right flush with the water, no buoyancy



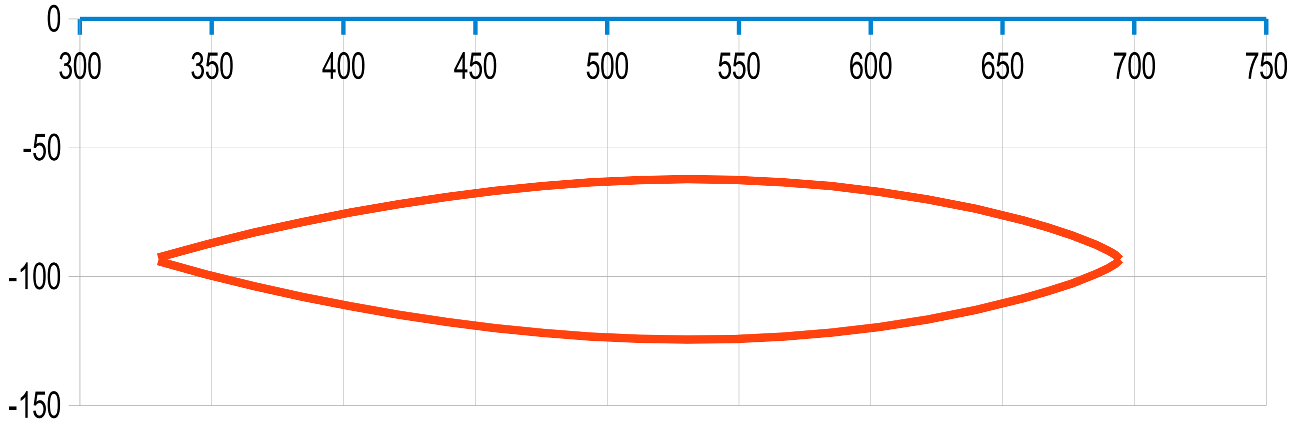
Z immersion = 0,5 >>> the axis of the float is at the waterline, the buoyancy of the float corresponds to half of its total volume.



Z immersion = 1,0 >>> the top of the float is just flush with the water, the buoyancy of the float corresponds to its full volume

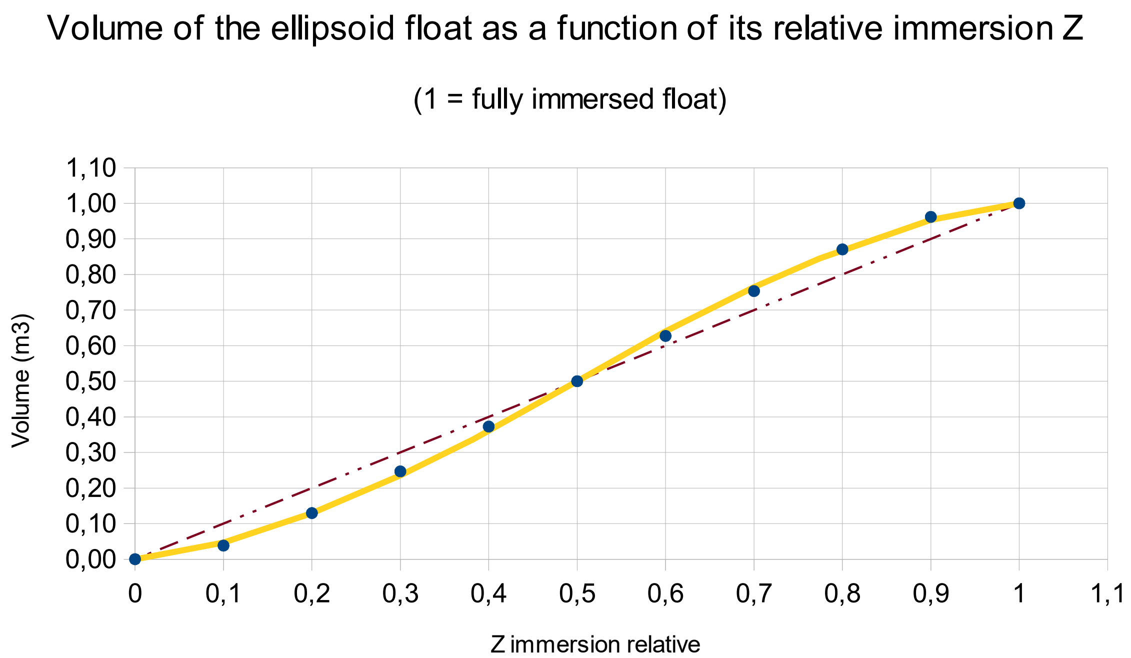


Z immersion ~ 2,0 >>> occurs for an heel angle of about ~ 25°



>>> in practice, **the field of the study is therefore Z relative immersion = 0 to 2**

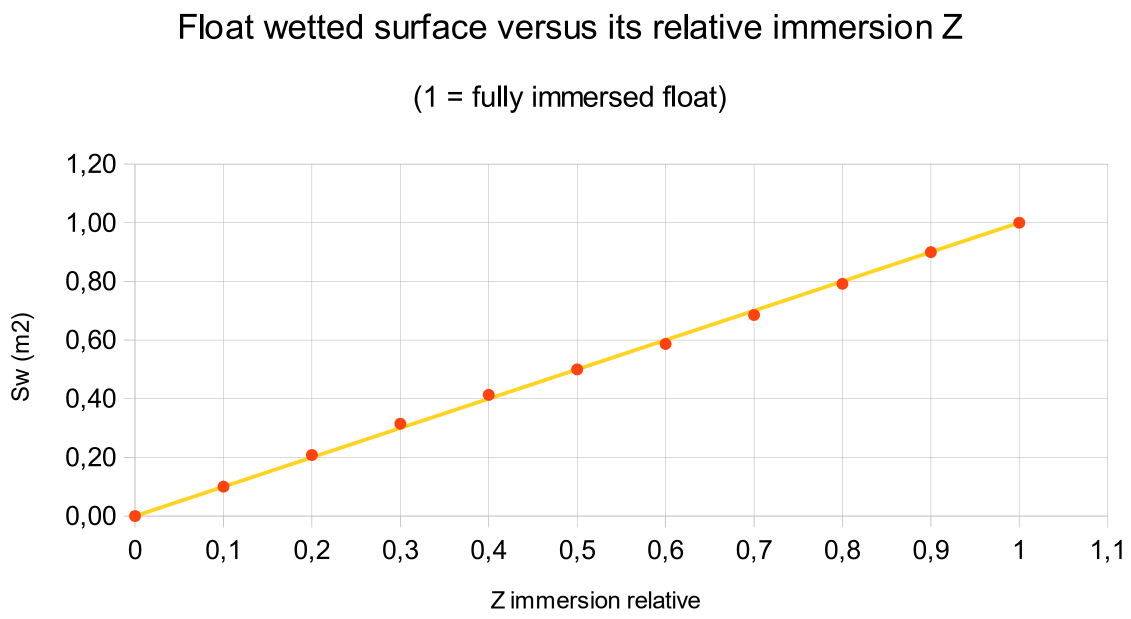
Variation of the volume and of the wetted surface of the float in function of its immersion :
(these data being involved in the evaluation of the wave and friction drags respectively)



>>> the blue dots are the volume calculations made, the yellow curve is the formulation introduced in the VPP.

For the perimeter of the ellipse (which has no analytical solution), I use the following approximate formula:

$$L \approx \pi\sqrt{2(a^2+b^2)-\frac{1}{2}(a-b)^2}$$



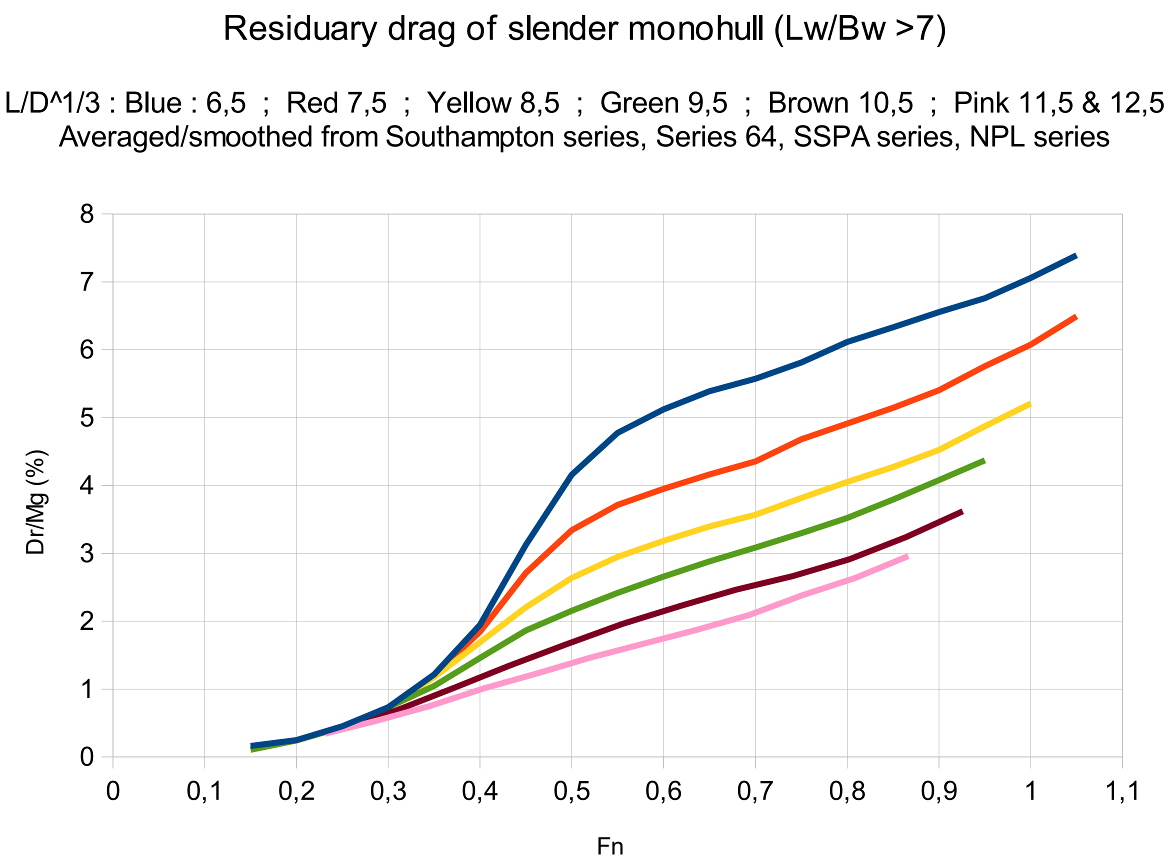
>>> the red dots are the surface calculations made, the yellow curve is the formulation introduced in the VPP.

2) **The speed V :** I use the float Froude related to its length L (= 3,65 m in our example) :
 - when upwind the speed can reach ~ 7 Knots, so a float Froude of 0,6 (the boat Froude being then ~ 0,37)
 - when downwind the speed can reach ~ 14Knots, so a float Froude of 1,2 (the boat Froude being then ~ 0,75)

3) **The wave drag :**

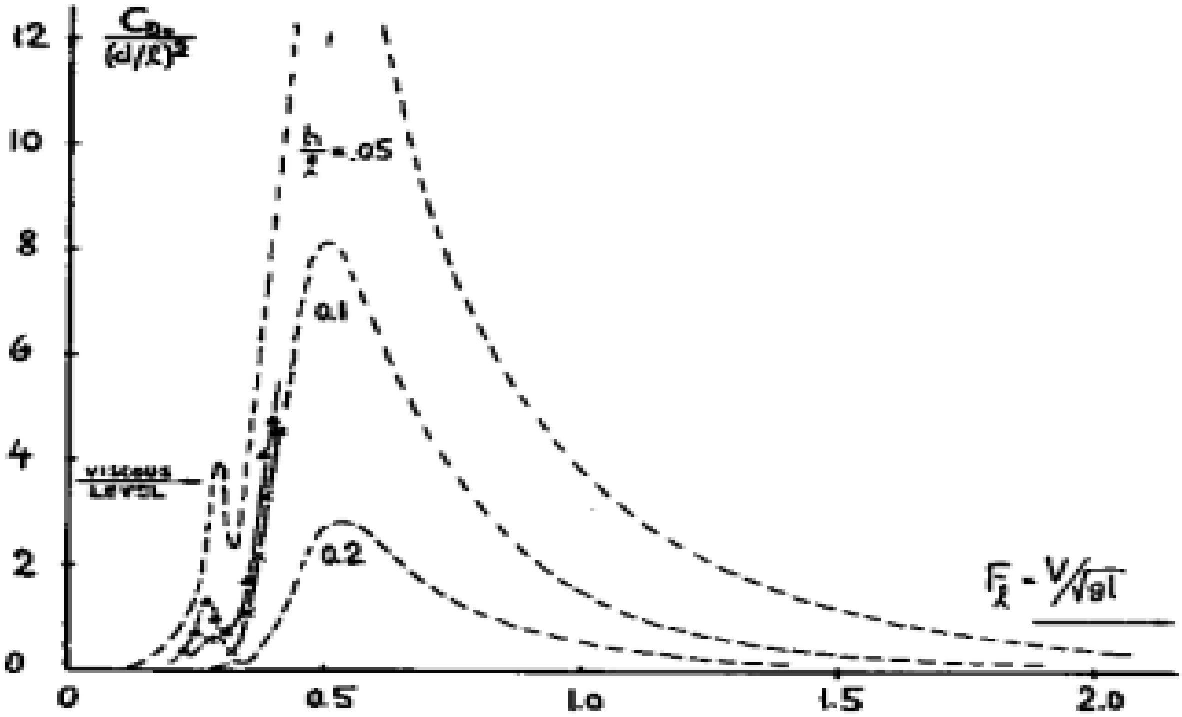
Two very distinct situations and an proposed connection :

When the relative immersion varies from 0 to 0,5 : the float can then be assimilated to a slender monohull whose L / B varies from 9.0 to 11.7 when Z varies from 0.1 to 0.5. For the estimate of the wave drag, one can use the curves deduced from the different series of model tests available, for which, when L / B > 7 and the Froude is between 0.3 and 0.9, only one parameter is sufficient for the wave drag estimation : L / D ^ (1/3)



Sources : model test series
« Southampton » series as reported in :
https://www.researchgate.net/publication/284260790_Resistance_experiments_on_a_systematic_series_of_high_speed_displacement_catamaran_forms_Variation_of_length-displacement_ratio_and_breadth-draught_ratio
Series 64, SSPA series and NPL series as reported in :
https://www.oossanen.nl/beheer/wp-content/uploads/2013/02/petervanoossanen_-_resistance_prediction_of_small_high-speed_displacement_vessels.pdf

When the immersion is ≥ 1 : the float can be likened to a submerged streamline 3D body for which the wave resistance in the vicinity of a free surface can be evaluated on the basis of data from the Hoerner Fluid-dynamic Drag (Fig. 18 on page 11-18) :



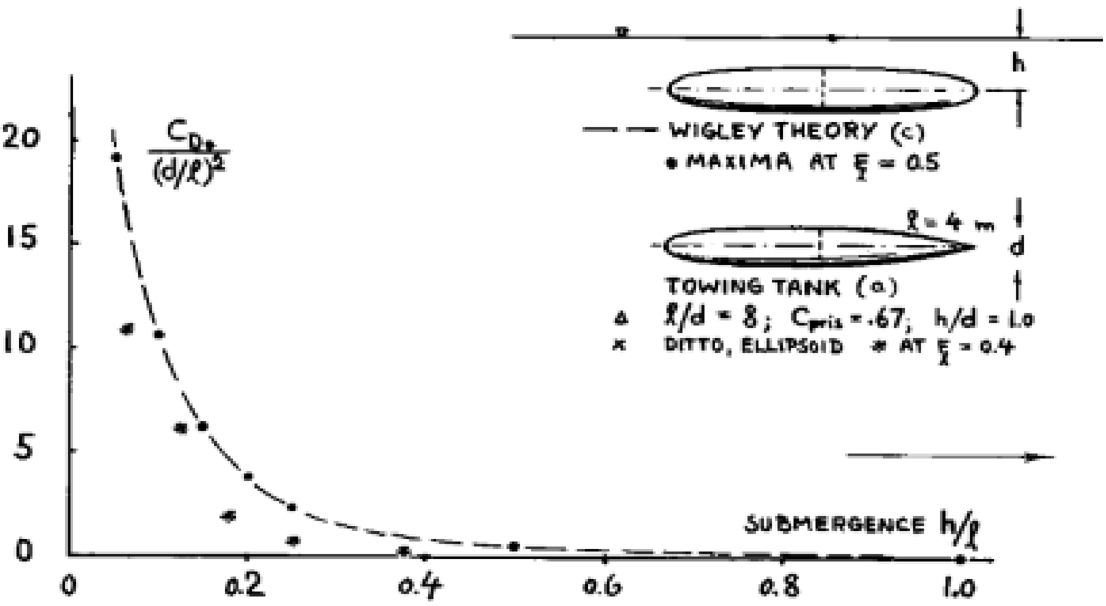


Figure 18. Wave-drag coefficient of submerged streamline bodies, as predicted by theory and as tested (21), as a function of Froude number and submergence ratio.

To note that :
it is the parameter h / L which is used to scale the curves, h being the depth of immersion of the axis of the float >>> the relation between h and our Z immersion is:

At Z immersion = 0,5 corresponds h = 0 : in this limiting case, Hoerner specifies that the wave resistance *"has a maximum at the surface when h ~ 0"* without specifying or quantifying this maximum in this case.

At Z immersion = 1,0 : corresponds in our example h = 0,311 m (F300) , so a **h/L = 0,085**

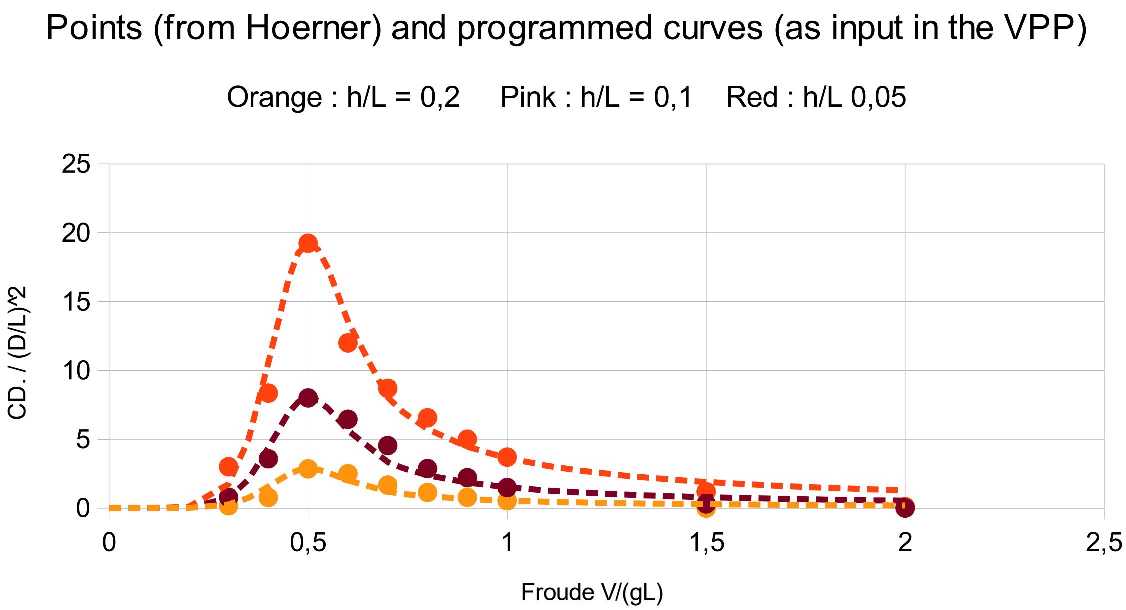
At Z immersion = 2,0 : corresponds to h = 0,933 m , so a **h/L = 0,256**

- it is not clear, and in my opinion unlikely, that the Hoerner data from model experiments can also cover cases of partial immersion when Z = 1 to 0.5

- The drag coefficient given is **CD. (d / l)^2**, for which **d** is the diameter of the streamline body >>> I assumed that for an ellipsoid body, we can validly replace **d** by **b**, the maximum width of the elliptical section, which is homogeneous with Mitchell's theory whose wave resistance is as **b^2**. Consequently, with volume and other equal conditions, to pass from an axisymmetric body of diameter **d** to an elliptical section of width **b = d / √2** and height **a = d √2** allows to divide by 2 the resistance of wave whereas the wetted area only increases by 1.089. It is therefore logical, when the two components of wave and drag are in play, to seek an ellipsoid form, whereas, if the body were very far from the free surface, the axisymmetric form would obviously be the optimum.

- the coefficient **CD.** with a point means that it is the frontal section of the body which is considered and the dynamic pressure **½ ρ V^2** dans la formulation.

Hoerner data have been digitalized and an interpolation formulation has been tuned :



4) The connection proposal when Z = 0,5 to 1 :

- The drag curve of the slender monohull is extended to Z = 0.6
- The tapered body drag curve is extended to Z = 0.9
- These two points at Z 0.6 and Z 0.9 are connected by a straight line

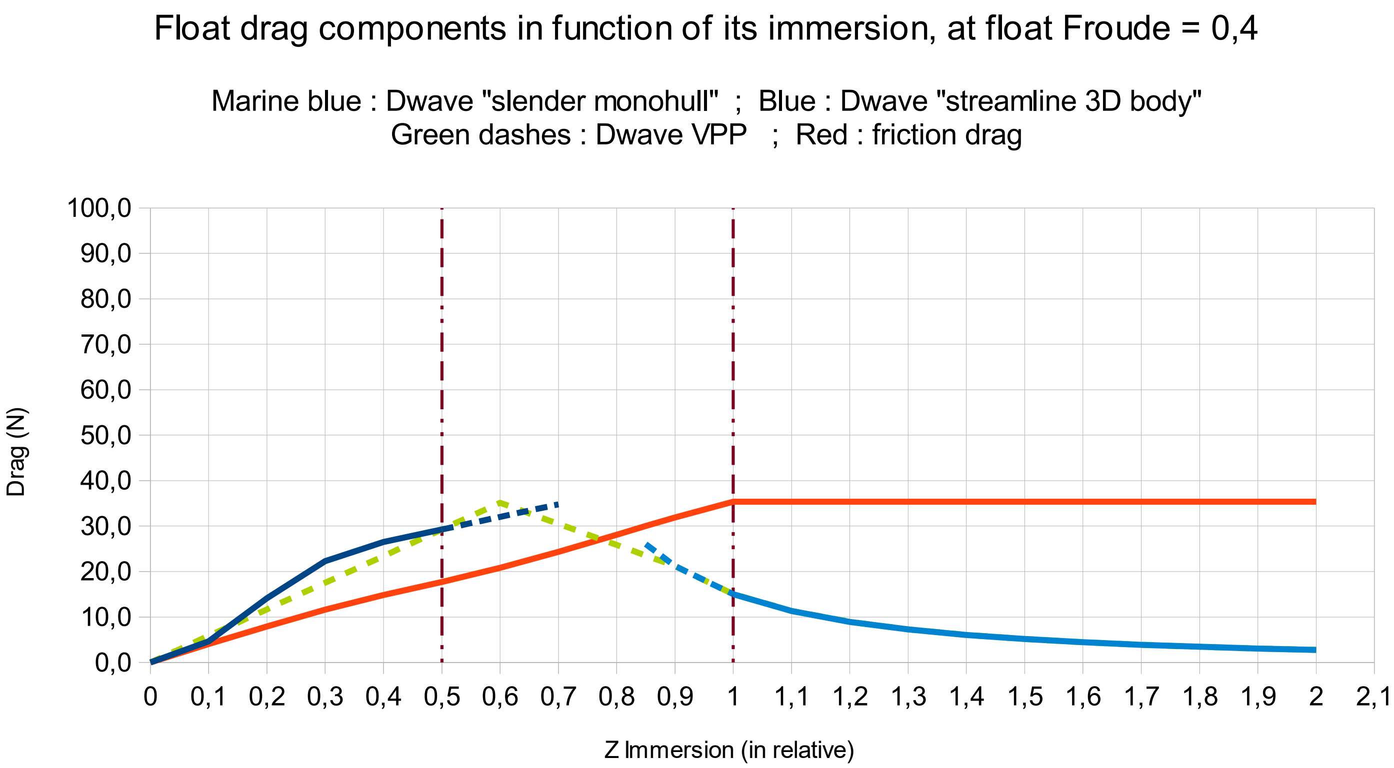
  Note: this type of connection generates a "pointed cap" shape which is not very physical but not bothersome for the VPP which iterates on one or other of the flanks of the connection "cap". The probability of being directly on the point is almost zero and can be avoided by changing a little the initial conditions, ie the wind force.

5) Result figures for the typical configurations

In the figures below, the two evaluations are drawn in continuous lines in their respective areas of validity, the wave drag of a slender monohull when Z = 0 to 0.5, the wave drag of an immersed streamline body when Z ≥ 1. The extensions of these assessments and the connection are drawn in dotted lines on the figures below. The formulation of the float wave drag, as introduced in the VPP, is in green dotted lines. To complete and compare the orders of magnitude involved, the friction drag (detailed below) is also calculated and plotted, in red line in the figures.

Each figure corresponds to a float Froude, so a serie of 0,4 to 0,9 , step 0,1 :

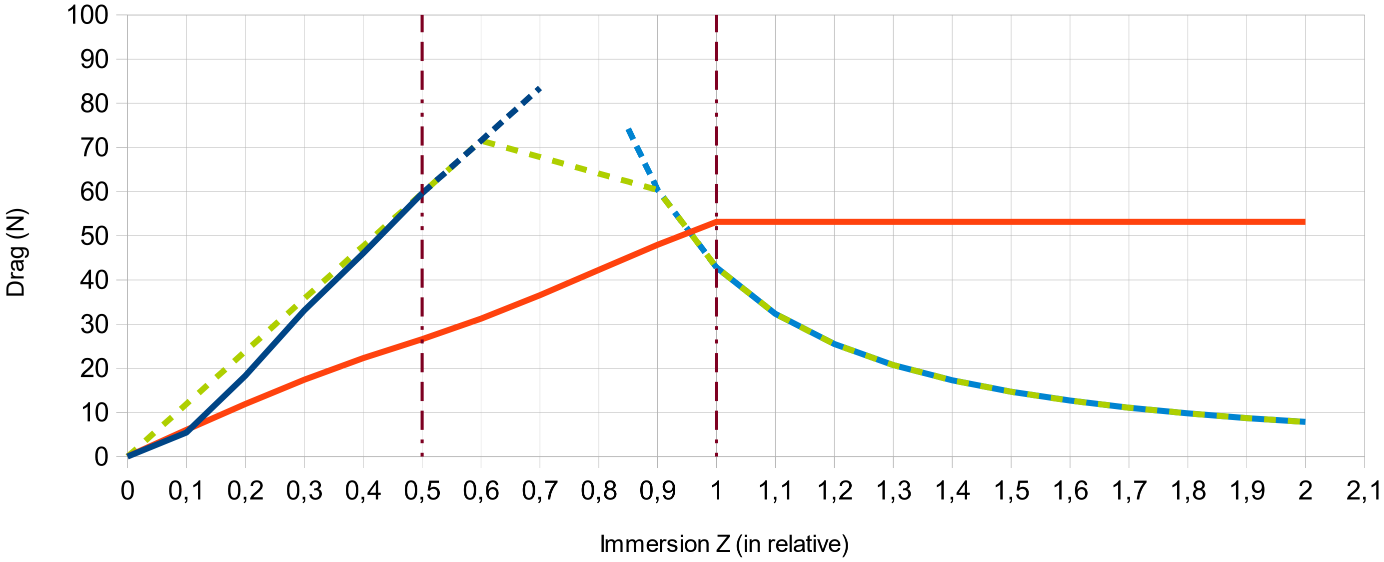
Fn	0,4	>> V (m/s)	2,39



Fn	0,5	>> V (m/s)	2,99

Float drag components in function of its immersion, at float Froude = 0,5

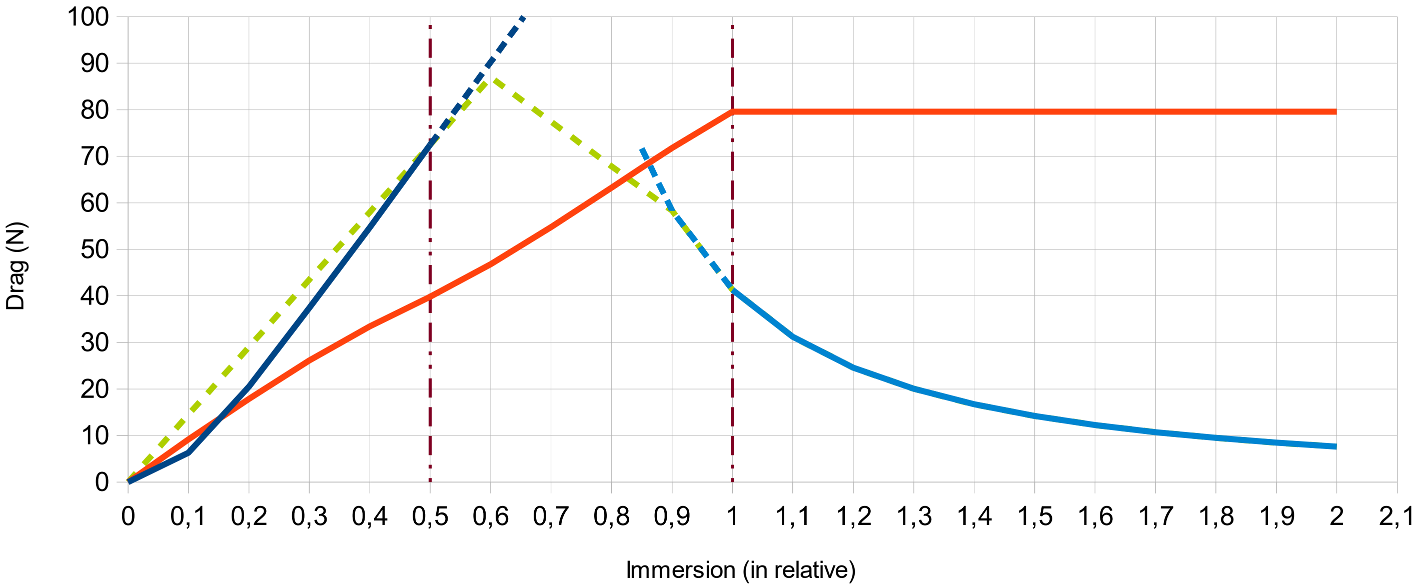
Marine blue : Dwave "slender monohull" ; Blue : Dwave "streamline 3D body"
Green dashes : Dwave VPP ; Red : friction drag



Fn	0,6	>> V (m/s)	3,59

Float drag components in function of its immersion, at float Froude = 0,6

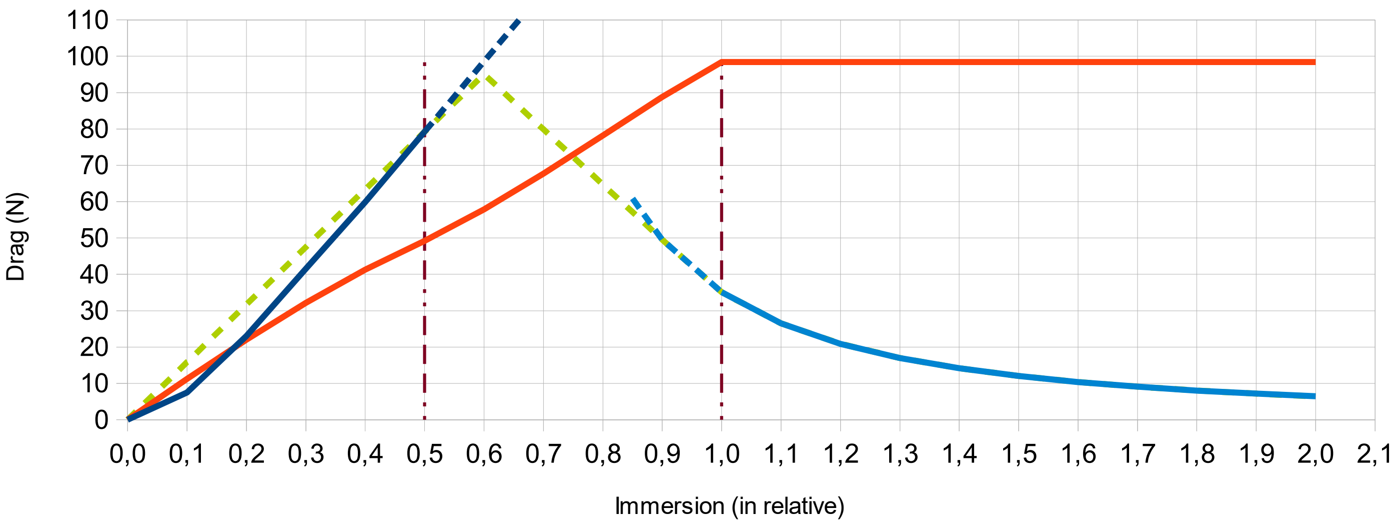
Marine blue : Dwave "slender monohull" ; Blue : Dwave "streamline 3D body"
Green dashes : Dwave VPP ; Red : friction drag



Fn	0,7	>> V (m/s)	4,19

Float drag components in function of its immersion, at float Froude = 0,7

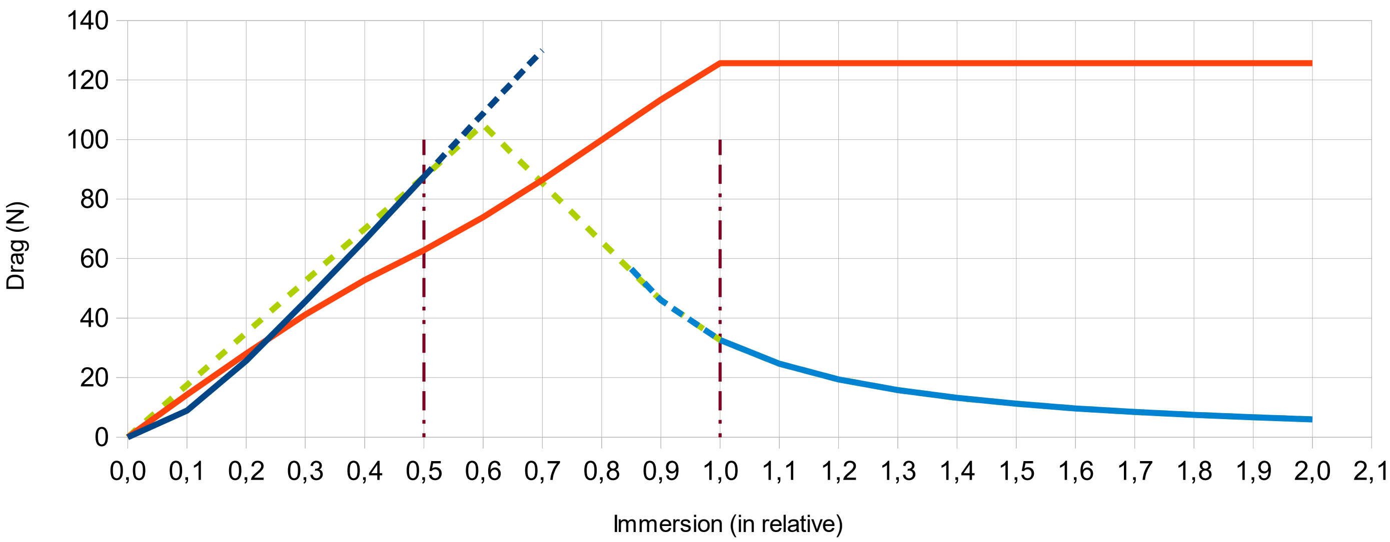
Marine blue : Dwave "slender monohull" ; Blue : Dwave "streamline 3D body"
Green dashes : Dwave VPP ; Red : friction drag



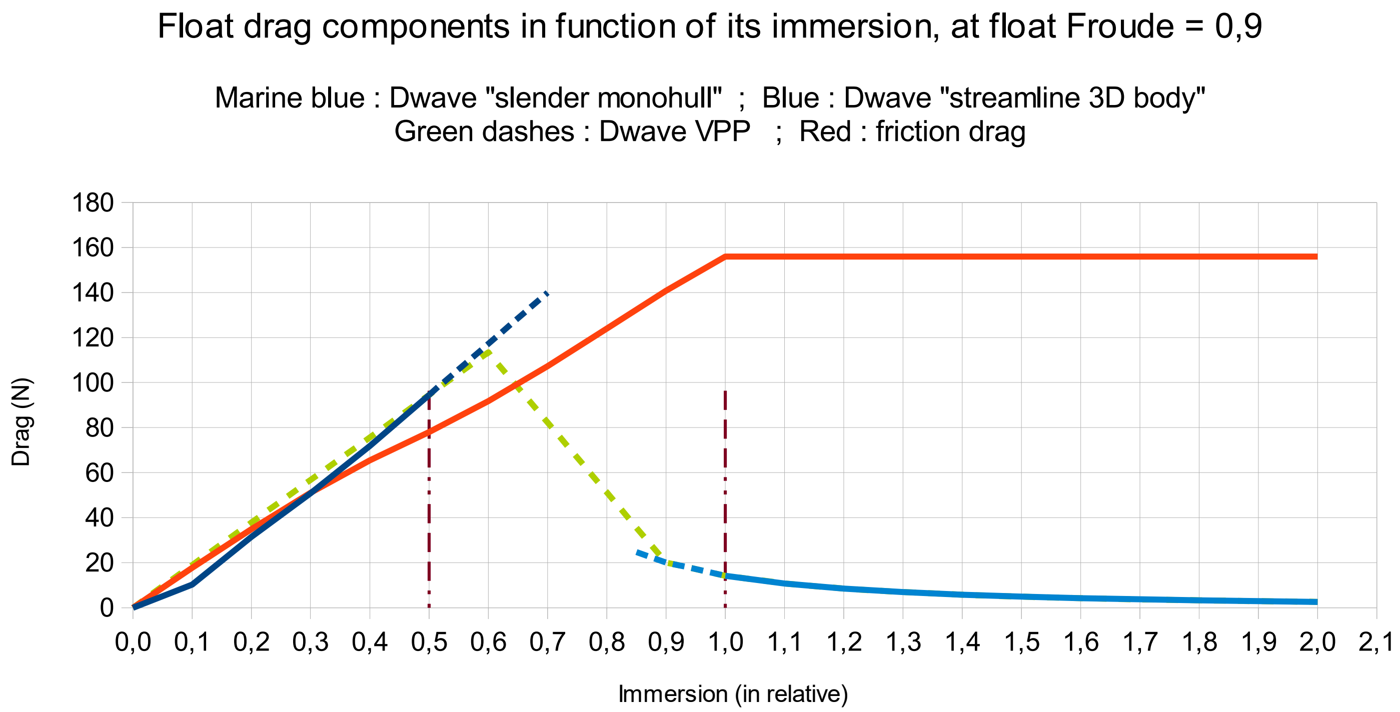
Fn	0,8	>> V (m/s)	4,79

Float drag components in function of its immersion, at float Froude = 0,8

Marine blue : Dwave "slender monohull" ; Blue : Dwave "streamline 3D body"
Green dashes : Dwave VPP ; Red : friction drag



Fn	0,9	>> V (m/s)	5,39



Note that in all cases, the wave drag of the streamline body at immersion Z = 1 is always less than that of the slender monohull at Z = 0.5, which seems to justify Hoerner's remark that *the drag "has a maximum when 'at' surface '*. The proposed connection overshoot this maximum, is it real or not, and if so how much, that is the question? It is this choice of connection which "digitally" makes the wind speed deficit upwind when the wind is too weak to fully immerse the float (maximum deficit 0.35 Nds when 6 to 8 Nds of wind with the float deployed)

6) Friction drag of the float

One uses the formula proposed by Hoerner for a streamline axisymmetric 3D body

$$C_{Dwet}/C_f = 1 + 1.5\,(d/l)^{3/2} + 7\,(d/l)^3 \qquad (28)$$

The coefficient **CDwet** signifying that it is the wetted surface **Sw** of the body which is considered and the dynamic pressure **½ ρ V ^ 2** in the formulation of the friction drag **Df**:

Df = Cdwet * Sw * ½ ρ V^2

Cf is computed with the usual formulation ITTC 57 : **0,075 / (Log(Re) -2)^2**
with **Re = V L /ν**

For **d** in the case of an elliptical section (Da, Db) , Hoerner recommends to take :
d = 0,5 (Da + Db)

L is the length L of the float

Annex A2 : Drag estimation of the support arm (« aka »)

The support arm is assumed to be a Naca profile section with a **t/c** of 9%, and made of carbon fiber. For the F300, it is a 400 mm chord x 36 mm thickness. Yet, no structure computations are carried out at this exploratory stage of the concept, dimensions are just an a priori to be consider within the system estimated mass (180 kg in the F300 version, of which ~ 45 kg for each arm, it is homogeneous with one arm 3.5 m transverse length in monolithic carbon fiber). It is understood that an engineering stage will be necessary and an iteration on this assumption if necessary.

This a priori definition of the support arm makes it possible to estimate the drag when the arm finds itself immersed. To simplify, we neglect the possible lift that the arm could provide and therefore is induced drag. We therefore only consider 3 components : wave drag, ventilation, friction.

Wave drag : estimation based on this Figure below proposed by Hoerner, using the Froude related to the profile chord.

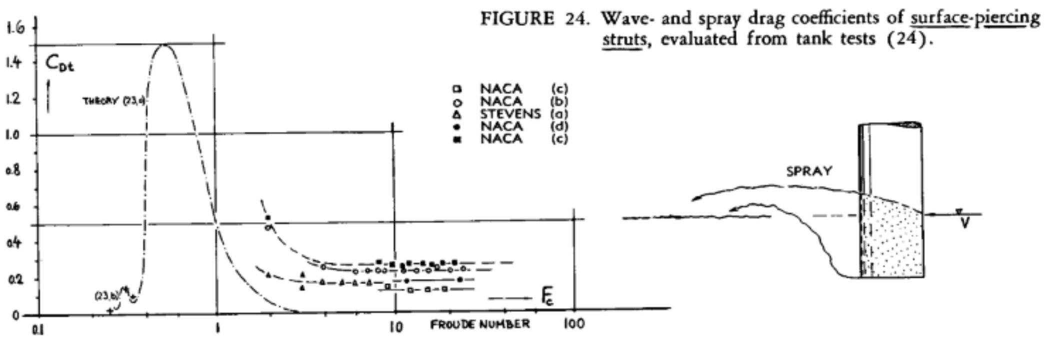
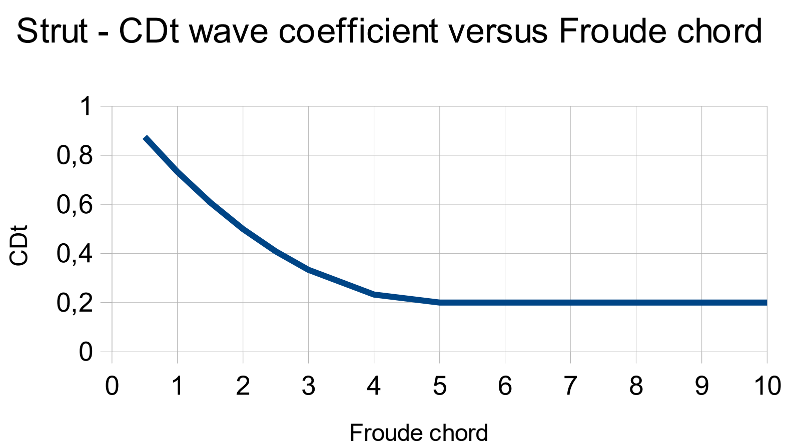


FIGURE 24. Wave- and spray drag coefficients of surface-piercing struts, evaluated from tank tests (24).

, from which we can deduce a conservative envelope estimate for the Froude Fc range involved in the VPP simulation, i.e. ~ 0.9 to 3.6



\>>> **Dwave = CDt * t * ½ ρ V^2** , **t** being the max thickness of the profile.

Spray drag :
Estimate based on the general formulation proposed by Hoerner, valid for Fc around 3 (ie the highest downwind speeds envisaged for the concept)

>>> **Dspray = 0,24 * t * ½ ρ V^2** , **t** being the max thickness of the profile.

Friction drag :
Similarly, based on a Hoerner formulation, also taking into account the contribution of the pressure drag in infinite medium:

CDs = 2 * Cf * (1 + 1,2 (t/c) + 70 (t/c)^4) , S being the profile surface (it is not Sw)

To be conservative, given the uncertainty on the friction / ventilation relationship of this arm always close to the surface, I added a coefficient 2 to this component:

>>> **Dfriction = 2* [CDs * S * ½ ρ V^2]**

Annex 3 – Provisional mass spreasheet of the various versions

The 4 versions (without floats, with F200, with F300, with F400) have the same light weight ship :
The mass of the float system is provisioned for :

- F200 : 120 kg
- F300 : 180 kg
- F400 : 240 kg

, and located at deck level and just ahead of the mast.

The differences in mass are compensated for by adding or removing mass from the ballast version depending, which keeps the light weight ship constant (3250 kg) but varies the vertical position of the ship center of gravity Zg (the variation on Xg is assumed to be negligible) .

	Masse (kg)	Zg (cm)
Version without floats	3250	0,461
of which ballast	*1192 (36,7 %)*	
Version with F200	3250	0,574
of which ballast	*1072 (33,0%)*	
Version with F300	3250	0,614
of which ballast	*1012 (31,1%)*	
Version with F400	3250	0,655
of which ballast	*952 (29,3%)*	

For the study with heel at stake, to this light weight is added an identical standard load of 160 kg (the crew) positioned in the cockpit (Xg ~ 2 m; Zg ~ 1,20 m) and windward (Yg ~ 1, 60 m).