Foil assist F3 performance evaluation – A numerical study

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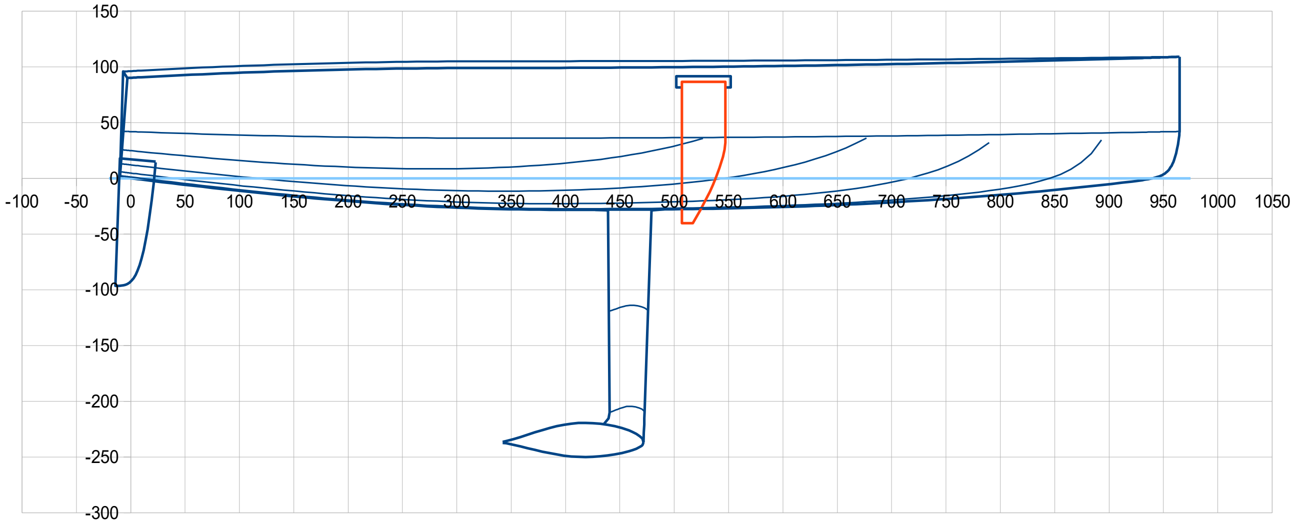
A numerical boat named **F3**, free interpretation inspired by the ***Beneteau Figaro 3***, is created to be used as support for this numerical study. The F3 performance upwind and downwind is evaluated :

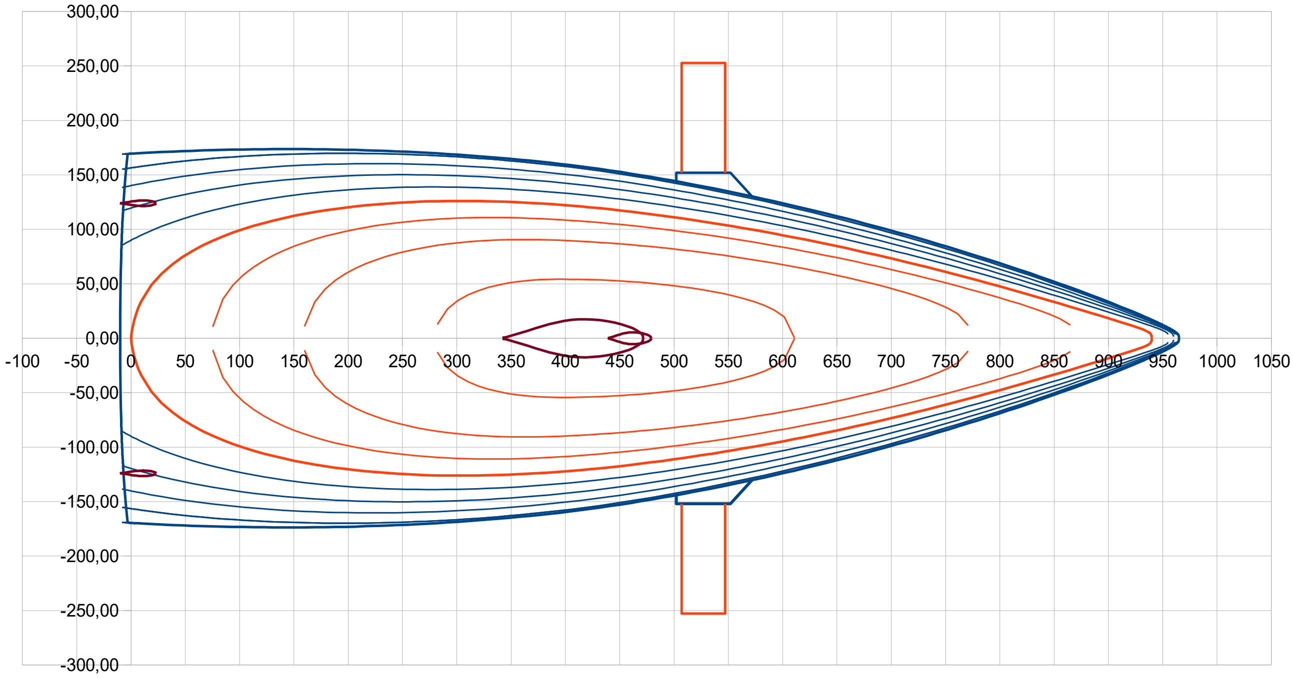
- with its « Chistera foils » and 2 crew (160 kg) sit winward.

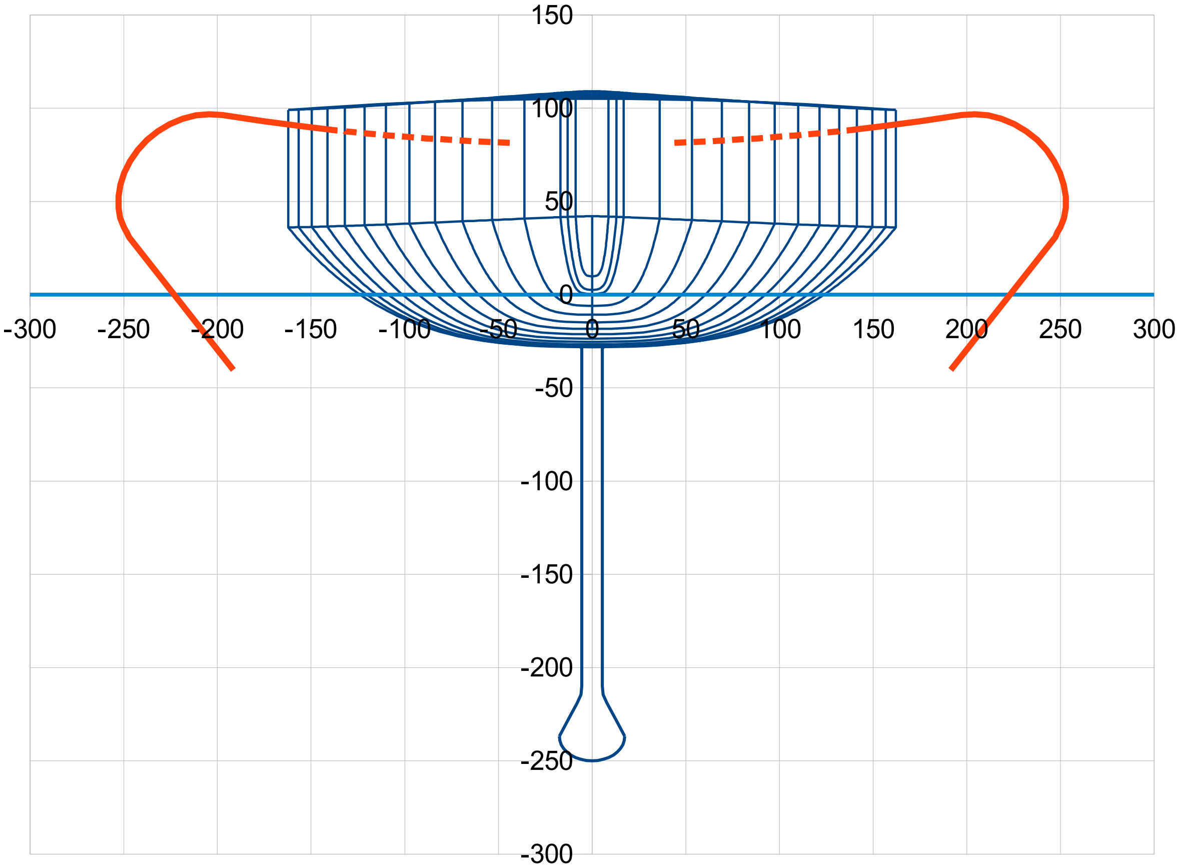
, and compared with 3 other numerical boats :

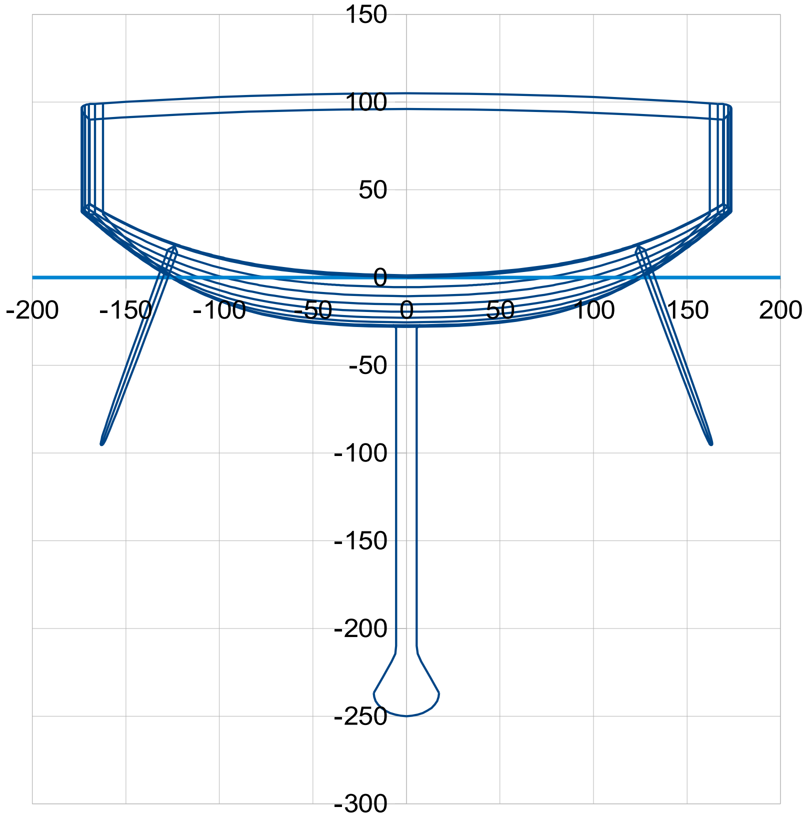
- **F3 wf** : i.e. F3 without foils and with 2 crew sit windward. The weight of the foils + the corresponding hull reinforcements can be estimated to ~ 120 kg, and for the **F3 wf** this weight is put as extra ballast in the keel bulb.
- **M32 8 crew** (free interpretation inspired by the ***Melges 32***) with 8 crew (640 kg) sit windward
- **M32 2 crew** with 2 crew (160 kg) sit windward

<u>The F3 boat</u> : Loa : 9,75 m ; Lwl : 9,40 m ; B : 3,47 m ; Bwl : 2,52 m ; Draft : 2,50 m
Displacement (light weight) : 2902 kg ; Ballast : 993 kg









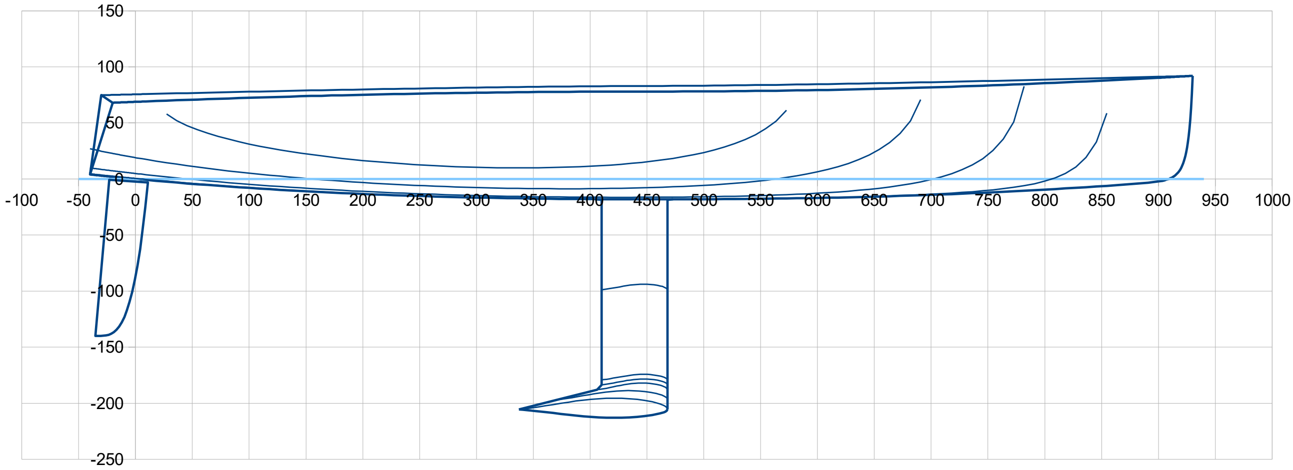
For the VPP study :

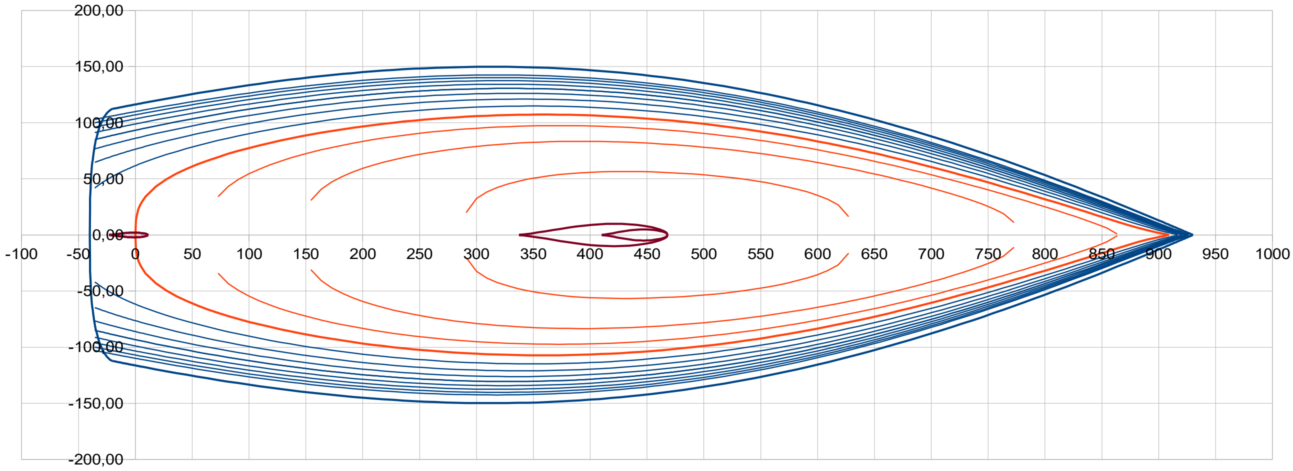
F3 : Displacement with 2 crew : 3062 kg, inc. ballast 993 kg and 2 crew 160 kg sit windward

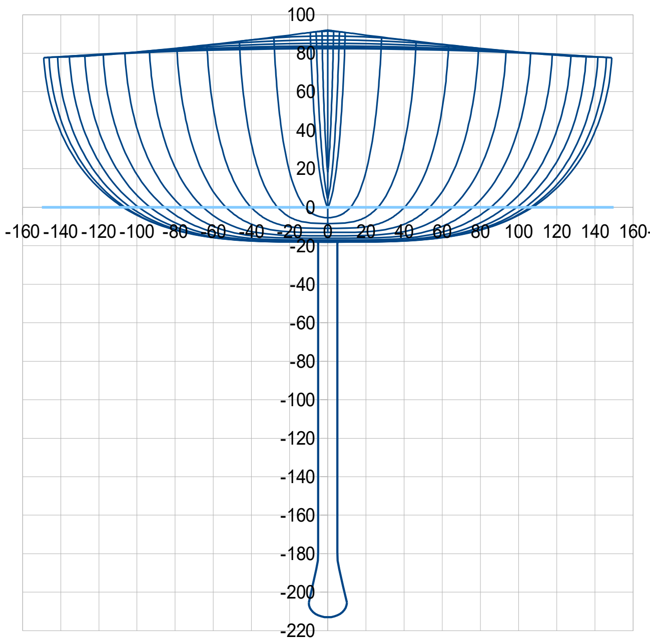
F3 wf : Displacement with 2 crew : 3062 kg, inc. ballast 1113 kg and 2 crew 160 kg sit windward

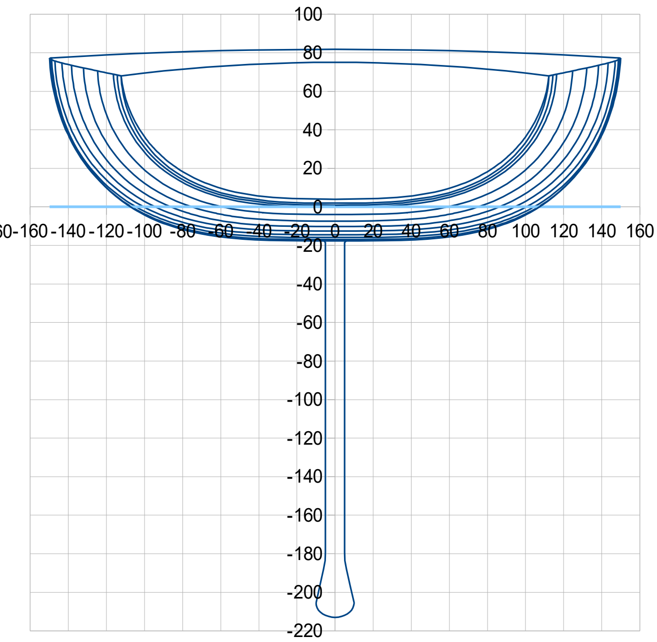
Lwl for the modelling, including the lenght under the transom >>> 9,50 m

<u>The M32 boat :</u> Loa : 9,70 m ;   Lwl : 9,09 m ;   B : 3,00 m ;   Bwl : 2,15 m ;   Draft : 2,13 m
Displacement (light weight) : 1712 kg ;   Ballast : 775 kg









For the VPP study :

M32 8 crew : 8 crew sit windward = 640 kg >>> Displacement : 2352 kg inc. ballast : 775 kg ;

M32 2 crew : 2 crew sit windward = 160 kg >>> Displacement : 1872 kg inc. ballast : 775 kg ;

Lwl for the modelling, including the lenght under the transom >>> 9,59 m

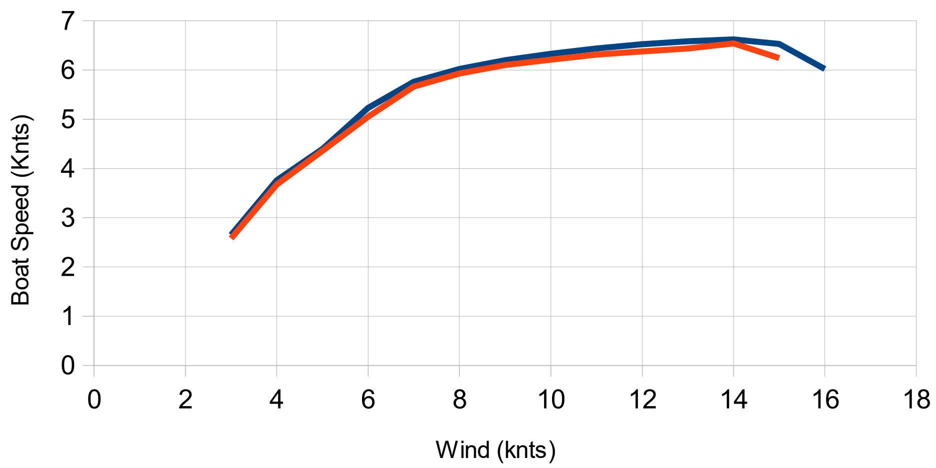
1. Comparisons in upwind conditions (twa 40° to 45°)

The simulation is done at constant sail surface and stopped when the speed begins to decrease and/or when the heel is over 30° . To go further would need a first reefing, but it is not done for the upwind simulation specifically, as it usually does not lead to significantly more speed due to the drag stiff slope at Froude > 0,35 (at the contrary, it is done for the downwind simulation here after, as we can overcome the drag hump and then the drag slope decreases when Froude is > 0,5). The twa is choosen between 40° to 45° for each case to obtain an optimum VMG.

1.1 Comparison F3 (with foils) / F3 wf (without foils)

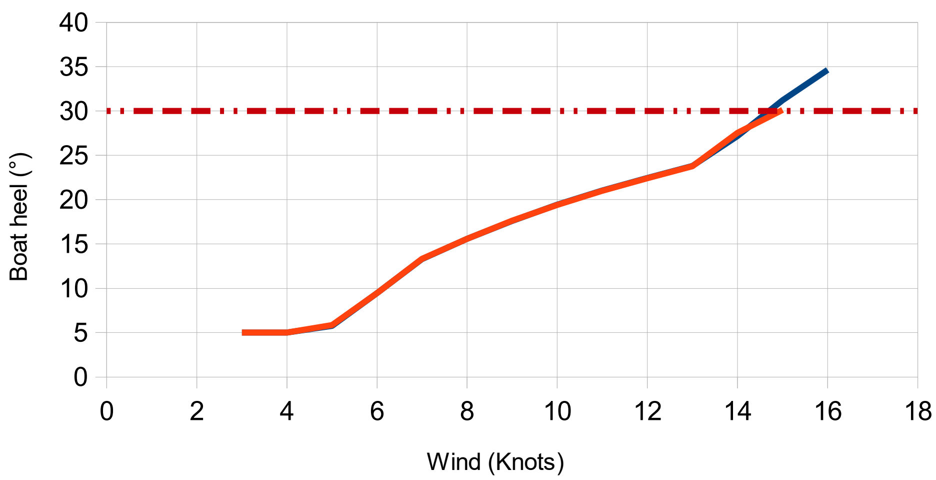
Boat speed upwind on calm water

F3 (with foils) : Red curve ; F3 wf (without foils) : Blue curve



Boat heel upwind on calm water

F3 (with foils) : Red curve ; F3 wf (without foils) : Blue curve

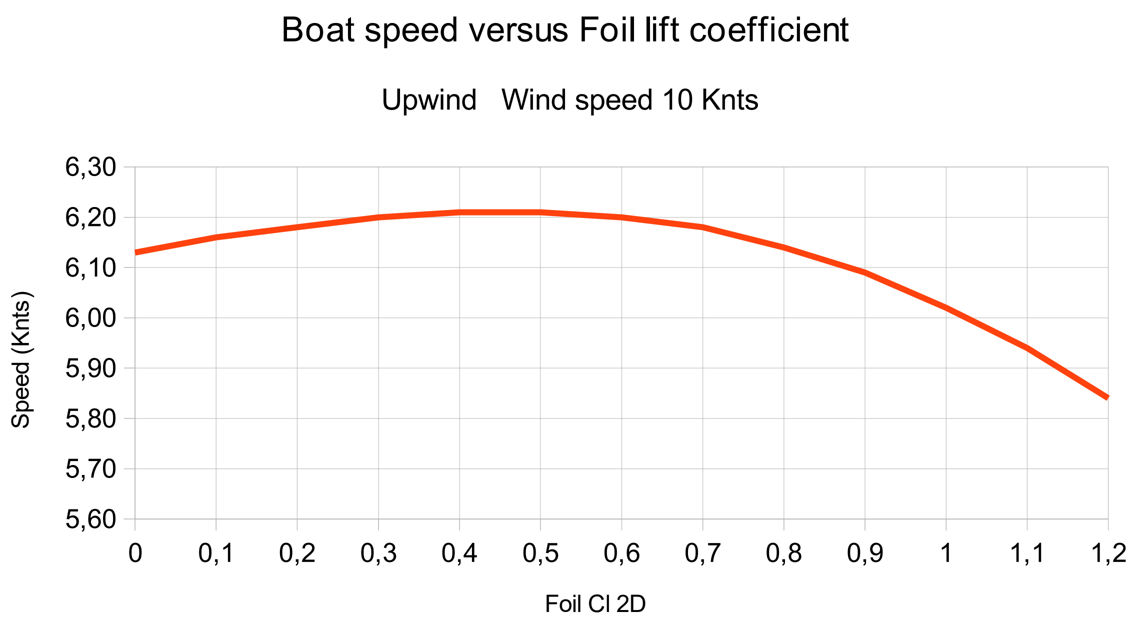


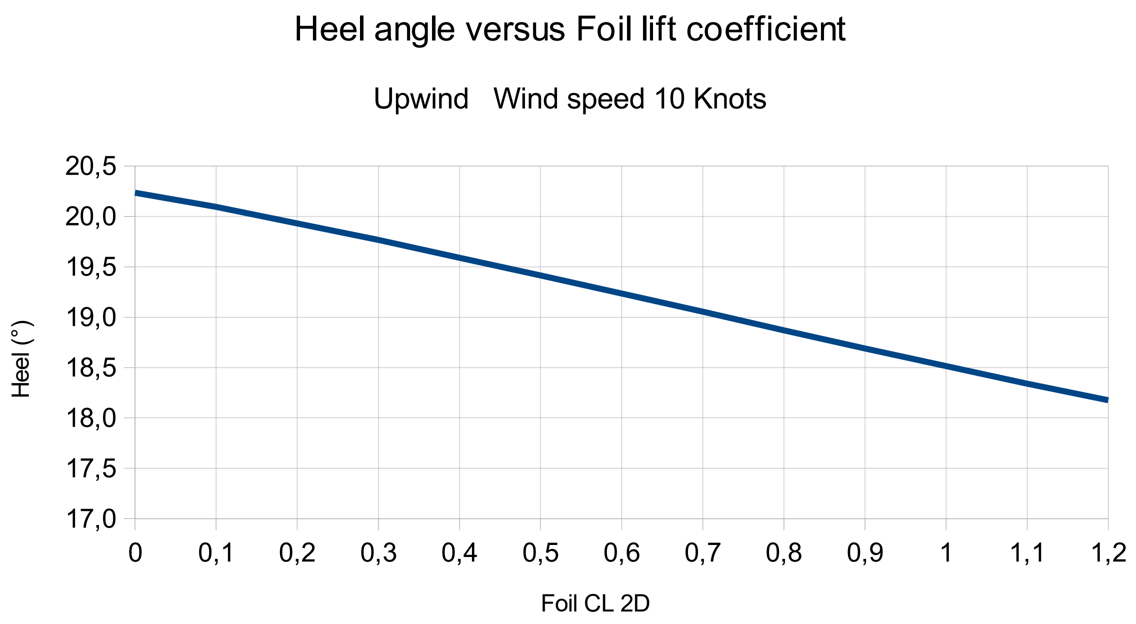
>>> Upwind, the speed is too low for the foil to provide a significant lift and so to influence the performance on calm water as well as the heel angle. To have 120kg more ballast in the keel bulb is

more efficient.
>>> On the other hand, beyond just the calm water performance, all Figaro 3 testers mentioned the beneficial influence of the leeward foil to soften the boat's movement on waves and thus help maintain good speed.

Test of various lift coefficients CL of the Foil : before adopting the right CL for each cases of the above VPP computations, a CL 2D typical range of 0 to 1,2 was tested with a path of 0,1 , from which the real CL 3D and corresponding Cd coefficients are computed due to the foil aspect ratio.

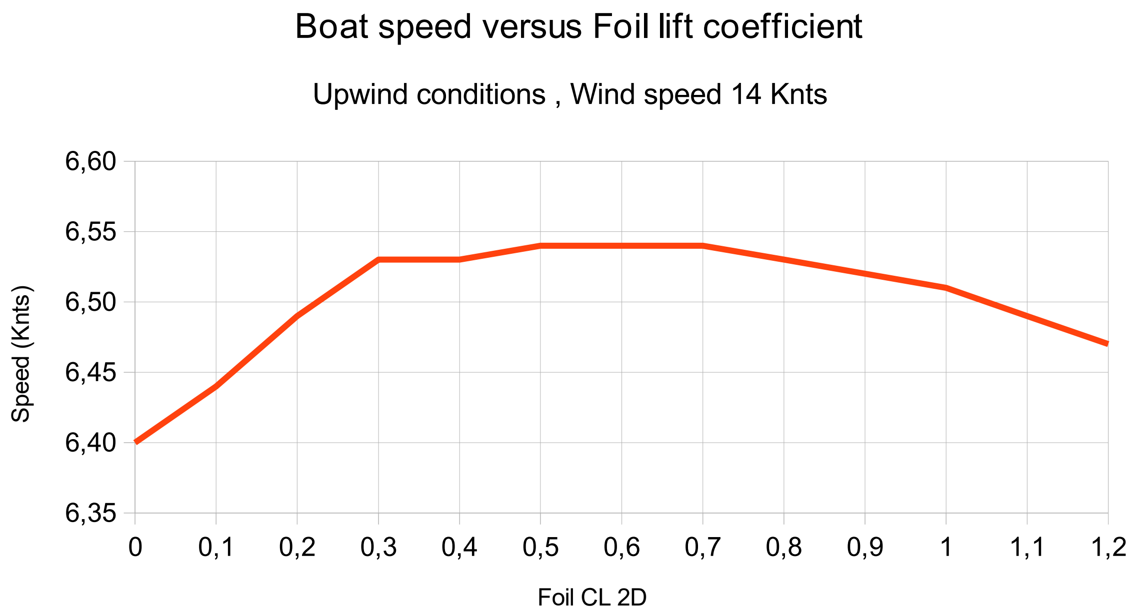
Example at wind speed 10 Knots :

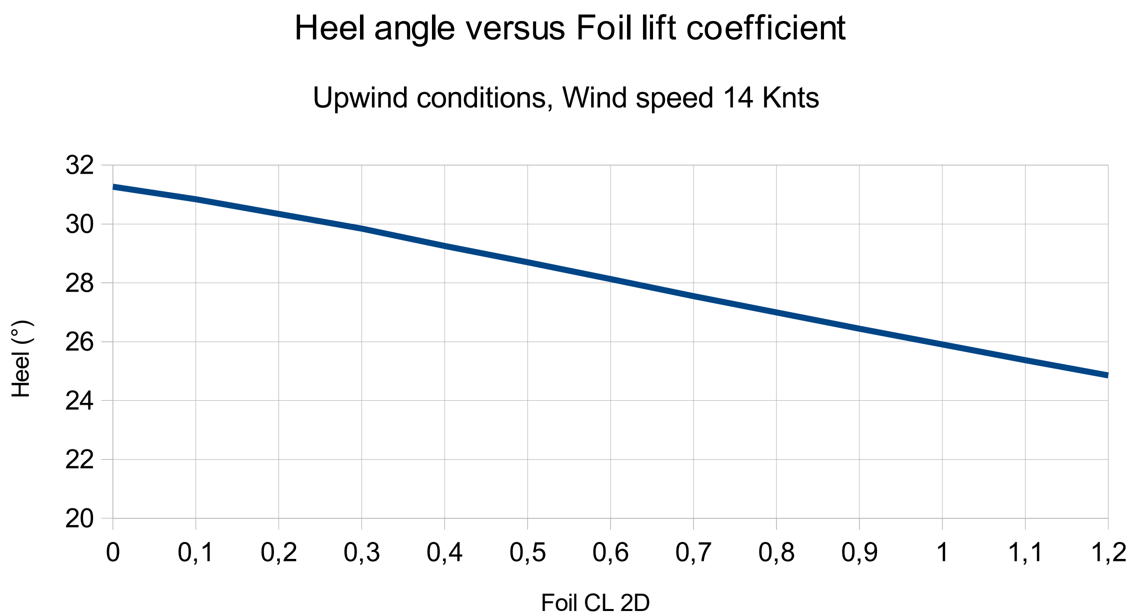




>>> at wind speed 10 Knts, there is clearly an optimum for a CL 2D = 0,5 , the use of a greater rake penalised the speed : one can loss 0,35 knots if using the maximum foil lift available CL 2D = 1,2.

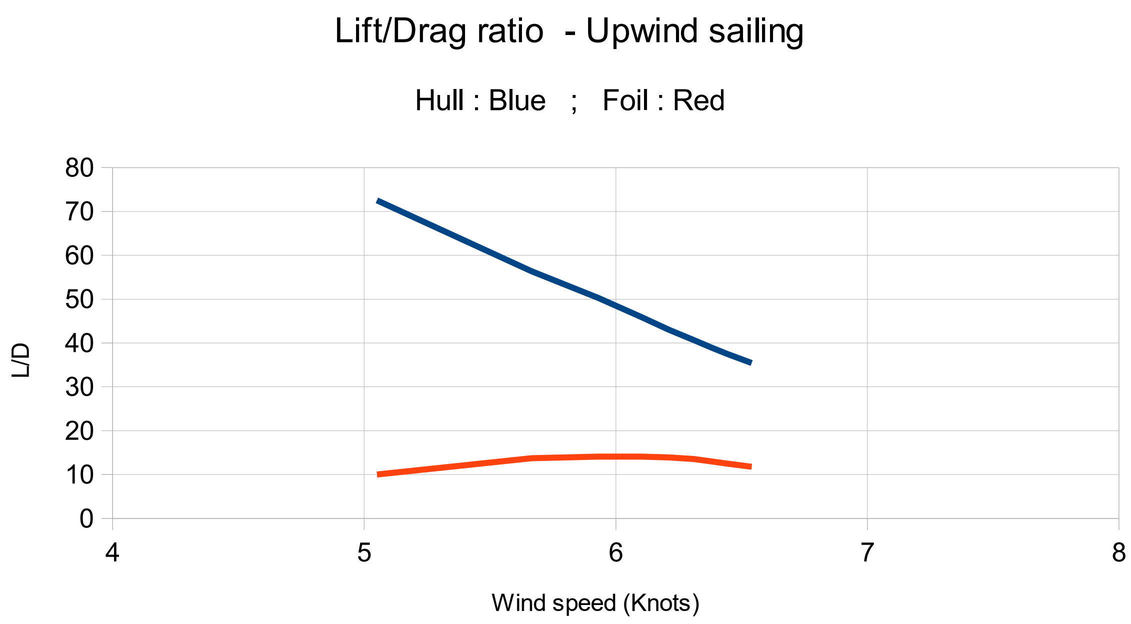
Example at Wind speed 14 Knots





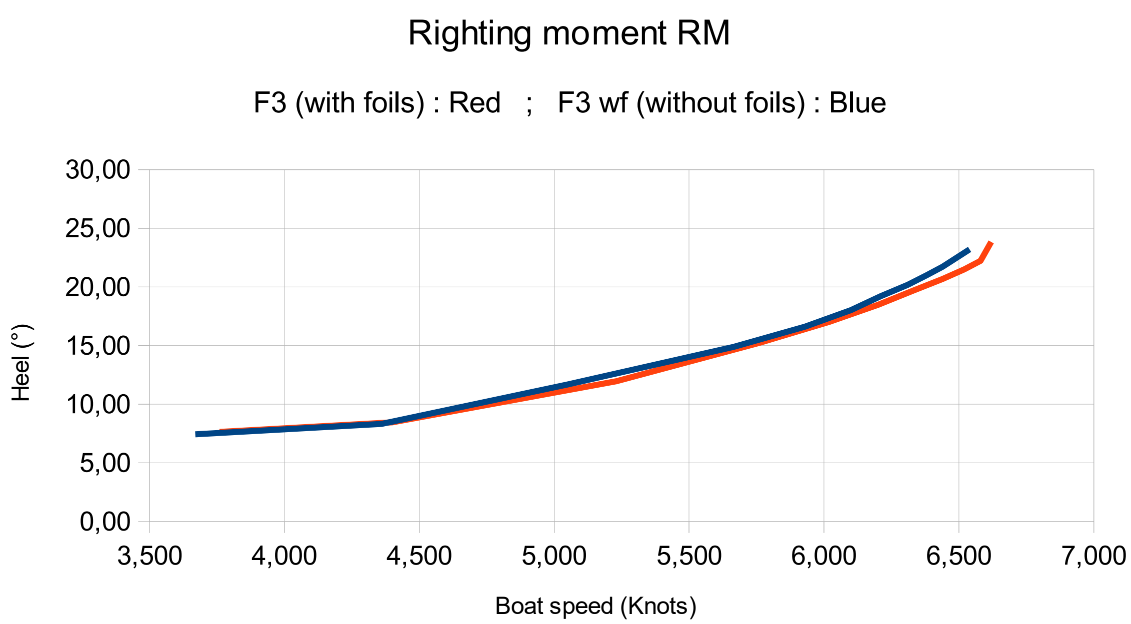
>>> with wind 14 knts for which the peak speed is reached, a large range of CL, from 0,25 to 1 has a very low influence on the speed (less than 0,05 knots difference) but a noticeable one on the heel angle. The optimum for both speed max and low heel is for CL 2D = 0,7 .

F3 : Lift/Drag ratio of the Foil and comparison with the one of the « remaining » Hull, i.e. the boat except its foil.



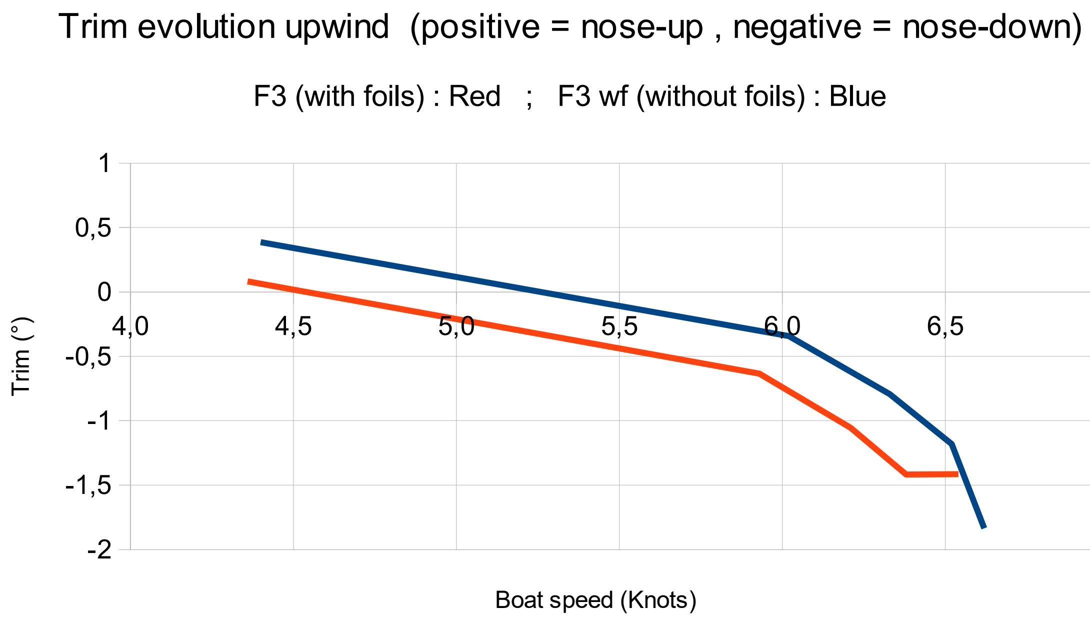
>>> The Lift /Drag ratio of the Hull remains a lot higher than the one of the Foil in the low speed range typical of an upwind sailing. So in that case a positive reward of the Foil use can rely only on the gain on RM (and a slight reduction of the Heeling arm) and as long as it cannot be reversed by the extra drag of the foil.

Righting Moment evolution with boat speed :



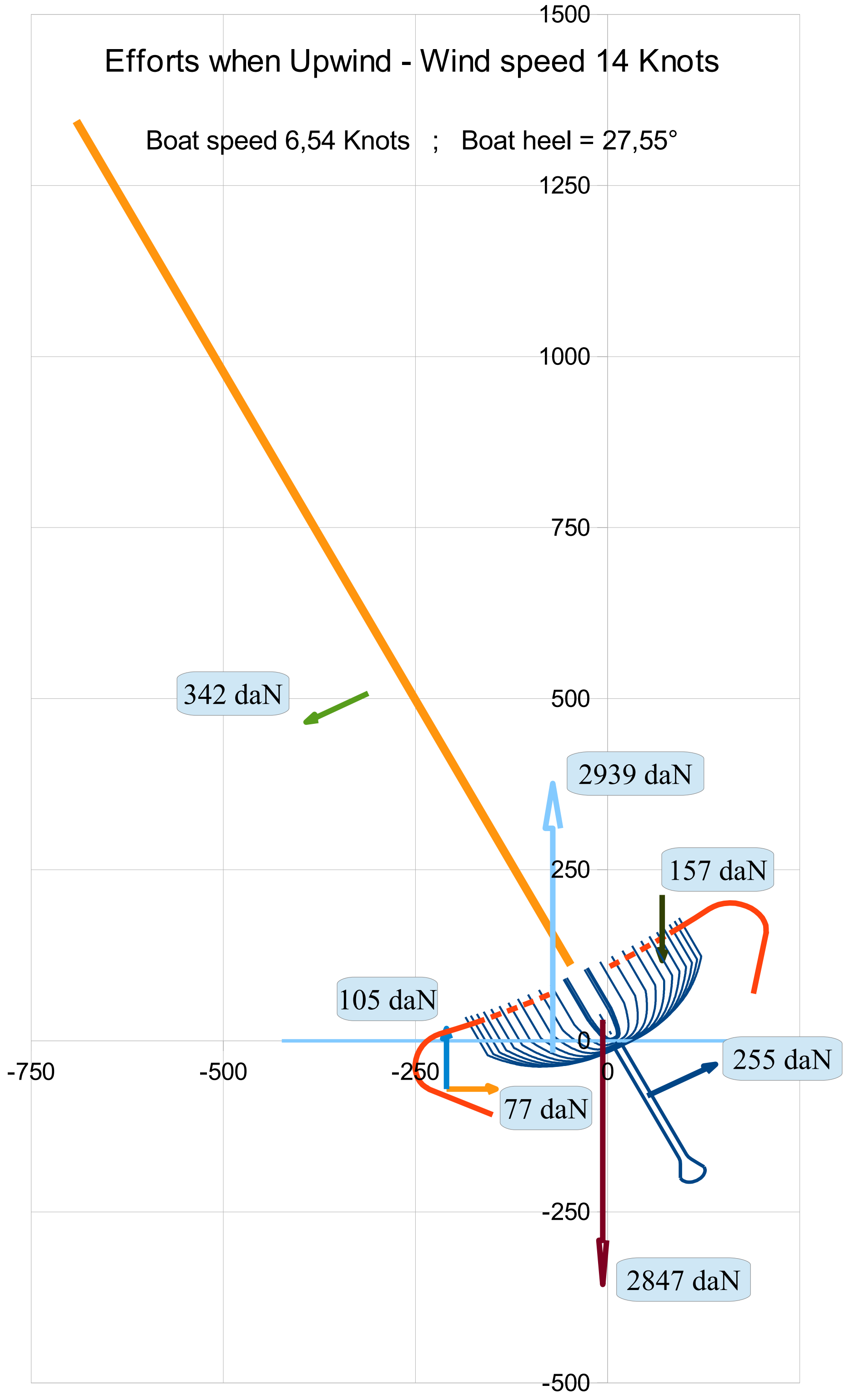
>>> The speed is too slow upwind for the foil to provide a significant extra RM. At the contrary, the F3 without foils, and with the saved 120 kg put as lead in the keel bulb, gives a slightly greater RM all along the speed range.

Trim evolution with boat speed :

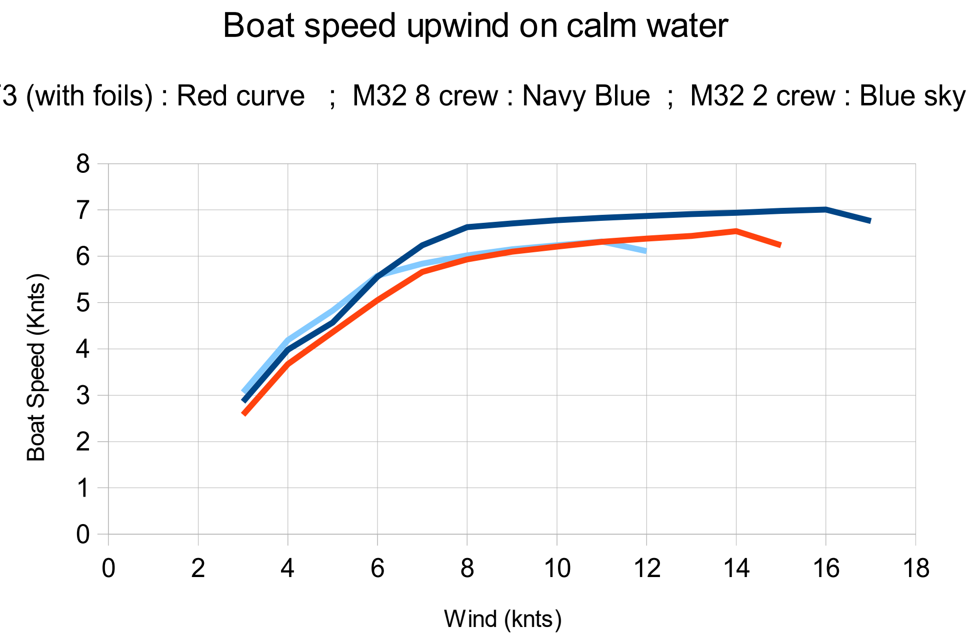


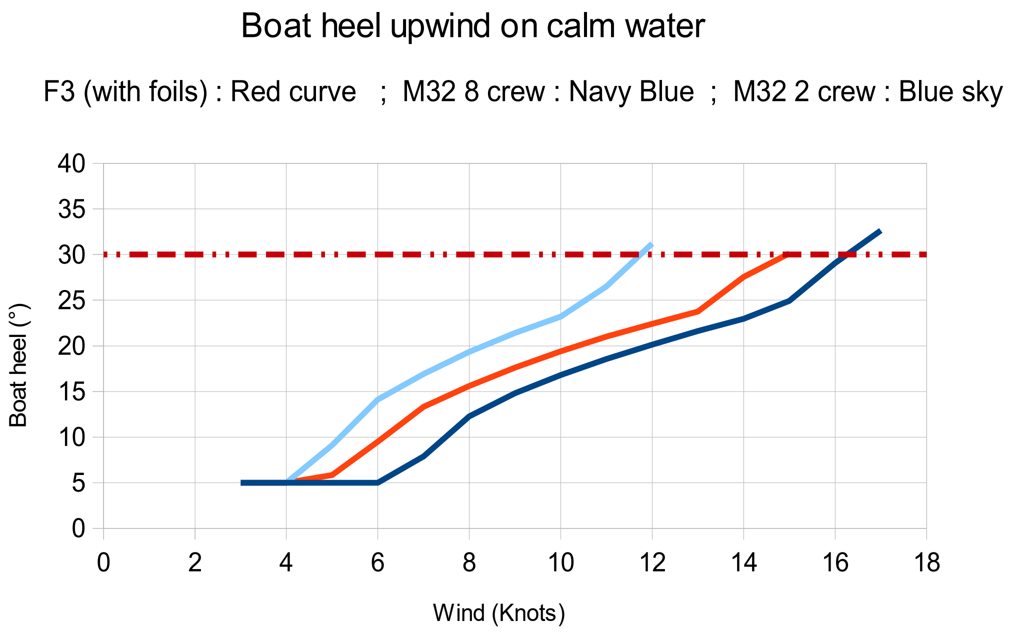
>>> The foil has a noticeable influence only at the peak speed, as it can prevent the trim to go beyond -1,5°, i.e. too much nose down.

Example of efforts distribution when upwind by wind speed 14 Knots



1.2 Comparison F3 / M32 8 crew and M32 2 crew





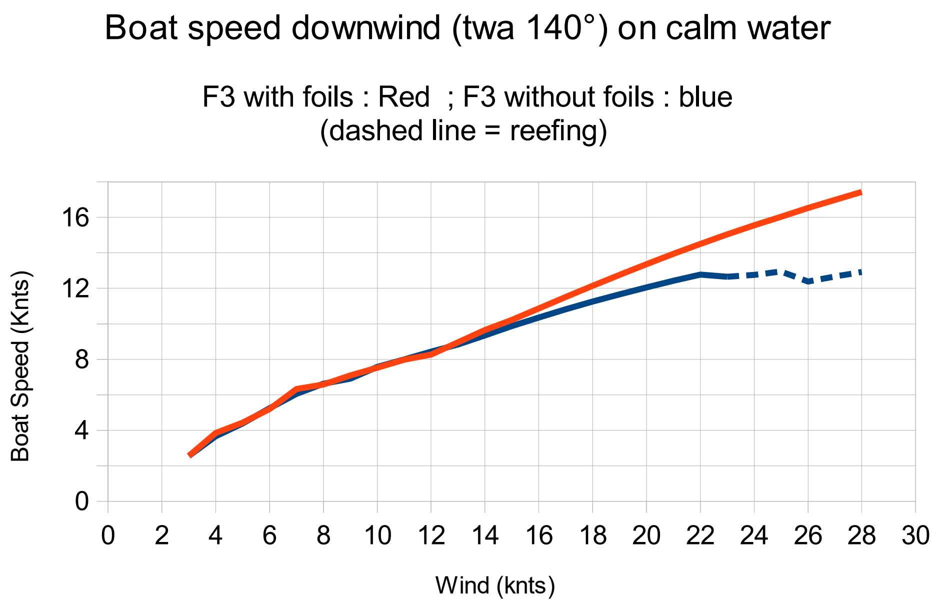
>>> M32 8 crew is signficantly faster than the F3, the biggest difference is for wind speed around 8 Knots (6,6 Knots / 5,9 Knots, ~ + 12%) , the peak speed is 7 knots / 6,5 knots (~ + 7 %). The light weight of the M32 associated with 8 crew sit windward make the difference.

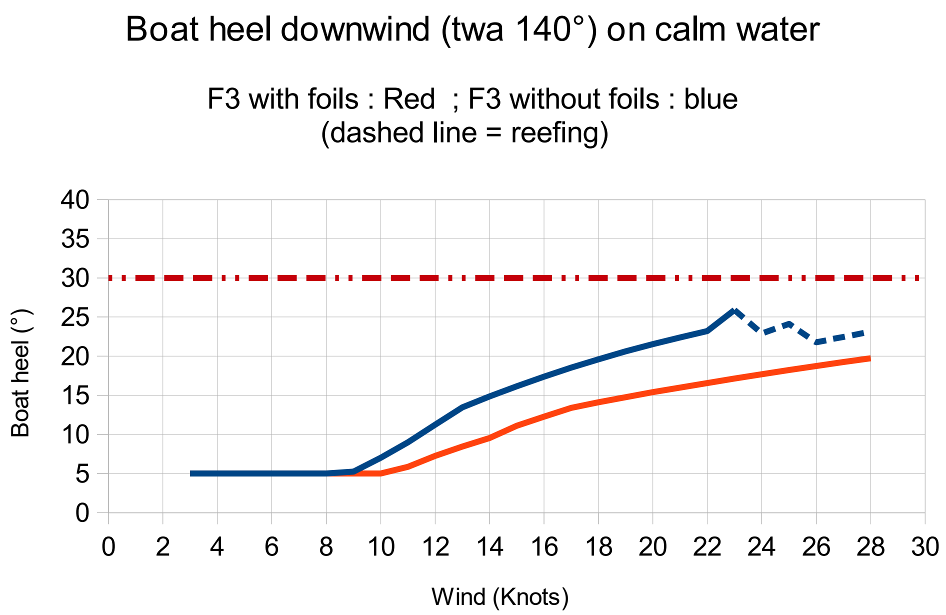
>>> The importance of the crew in the performance of the M32 is highlighted by the comparison 8 crew / 2 crew : the 2 crew version is faster by light winds < 6 knots as expected, but then strongly disadvantaged by its lack of RM and the peak speed before the first reefing is 6,3 Knots, reached for wind speed 11 Knots. For wind speed 8 to 11 knots, the speeds of F3 (2 crew) and of M32 (2 crew) are similar, but with the advantage of 4° to 5° less heel angle. For wind speed over 11 knots, F3 shows a greater speed and a delayed first reefing.

2. Comparisons in downwind conditions (twa 140°)

The simulation is done for a True Wind Angle fixed to 140°, up to wind speed 28 Knots, and when necessary the nominal sail surface is reduced by steps : 100% >> 75% >> 50%

2.1 Comparison F3 / F3 wf

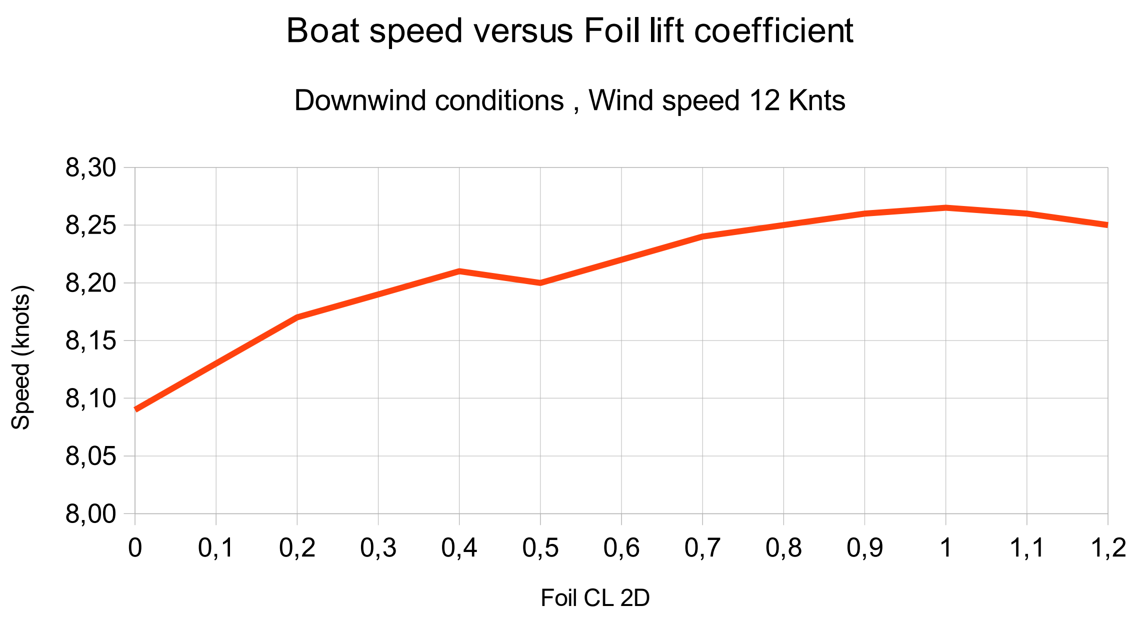


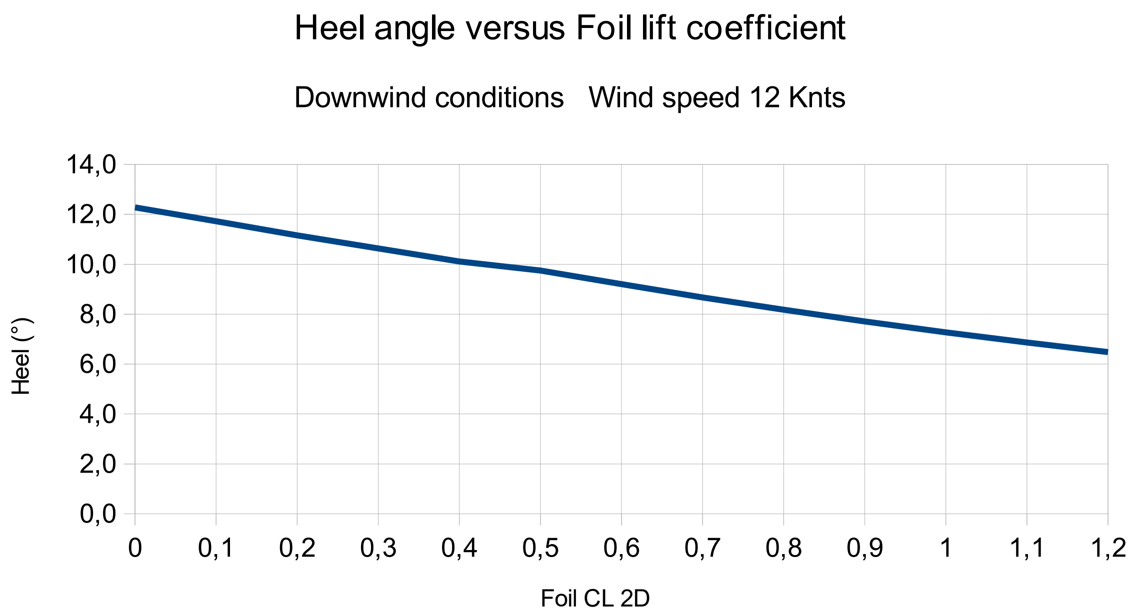


>>> From 16 Knots wind speed, F3 shows a greater speed, up to 4 Knots more when around 26-28 knots wind speed : F3 ~ 17 knots / F3 wf ~ 13 Knots.
>>> F3 can maintain its 100% sail surface up to 28 Knots wind speed, F3 wf should reduced its sail surface from 23 Knots.
>>> F3 has a lower heel angle, mostly 6° less by medium to strong winds, for example 17° instead of 23° for 22 knots wind speed.

Test of various lift coefficient CL of the Foil :

Example at wind speed 12 Knots

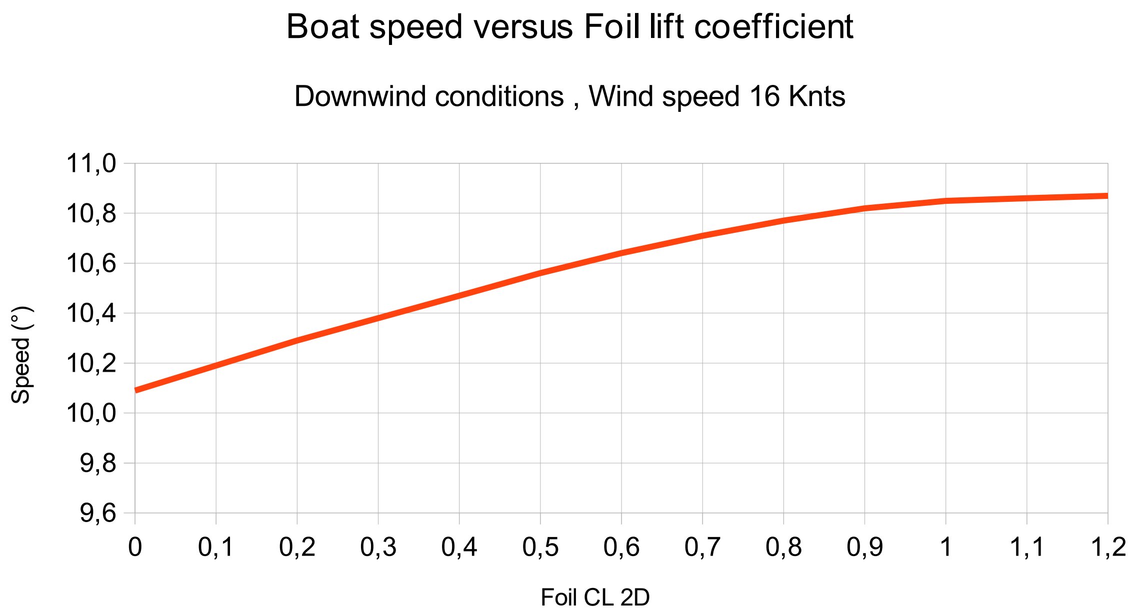


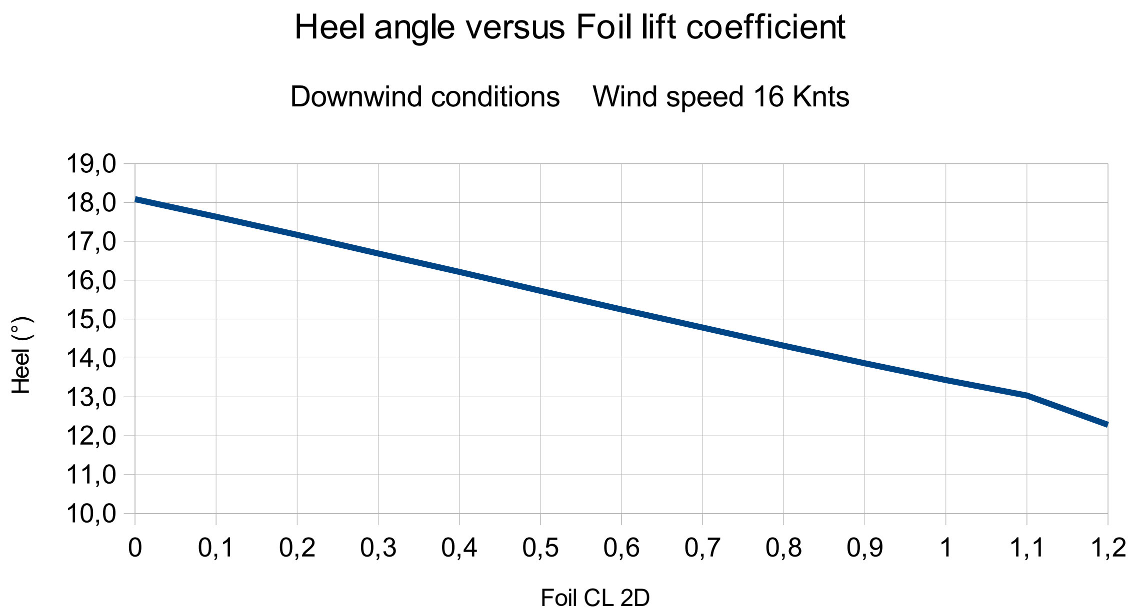


>>> By light-medium winds (here 12 Knots), the optimum lift coefficient appears to be 1,0 of the equivalent CL 2D, not necessary to use the maximum available 1,2.

>>> The difference in boat speed when compared with CL 2D = 0 is only 0,2 Knots, very small, demonstrating that the boat speed is too slow for the foil to make a difference.

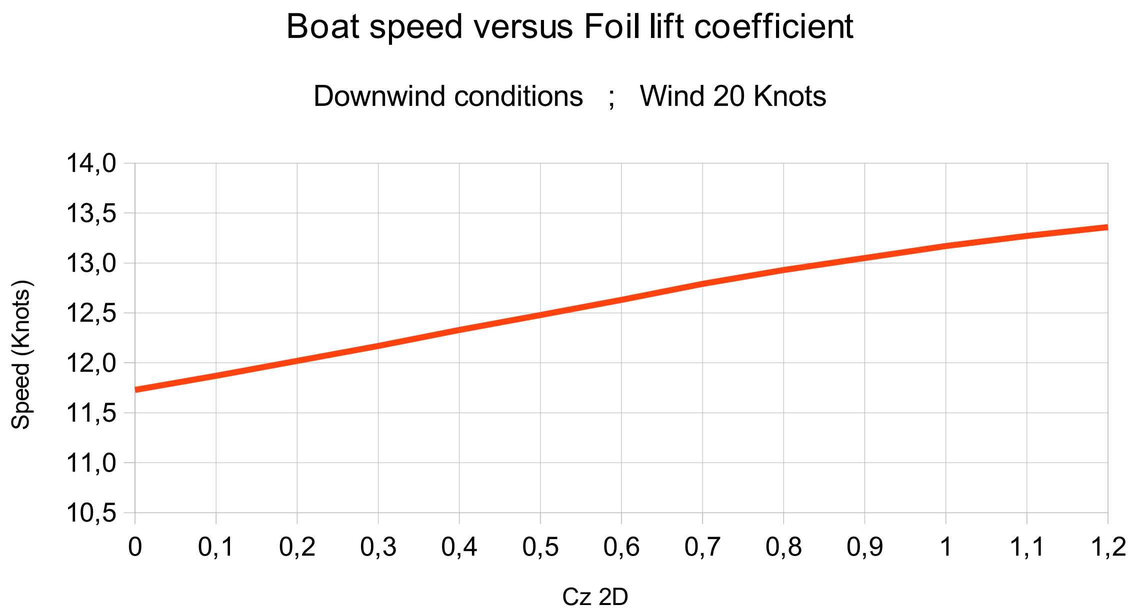
Example at wind speed 16 Knots :

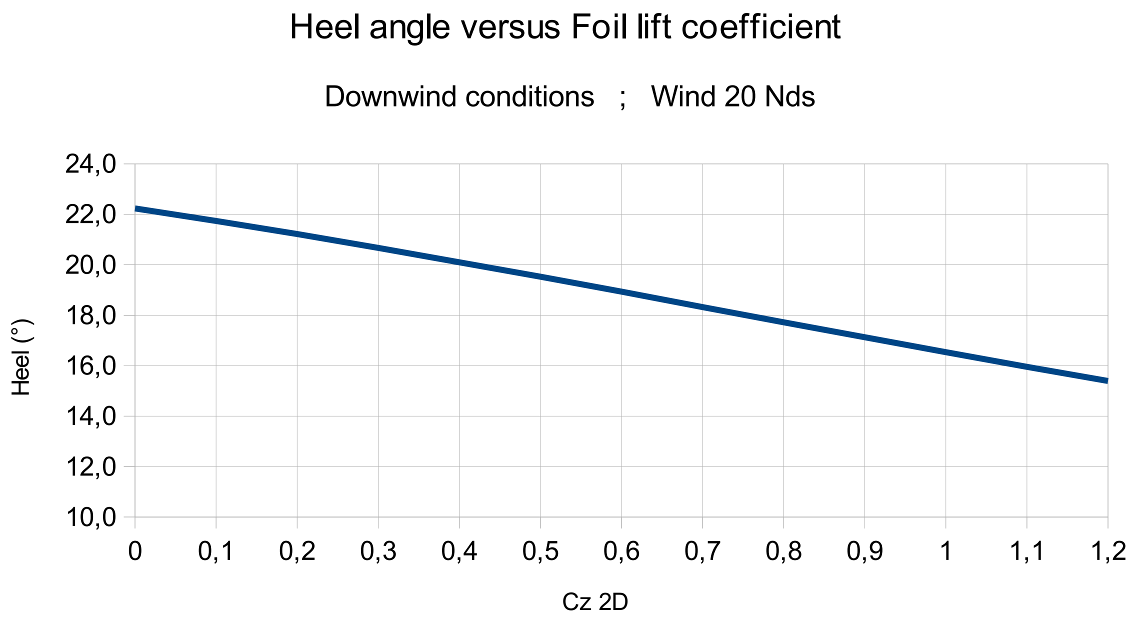




>>> From medium winds 16 Knots, it is worth to use the foil maximum lift coefficient, i.e. the equivalent CL 2D = 1,2 , which leads to a speed over 10,8 Knots and an heel angle of around 12° - 13° .

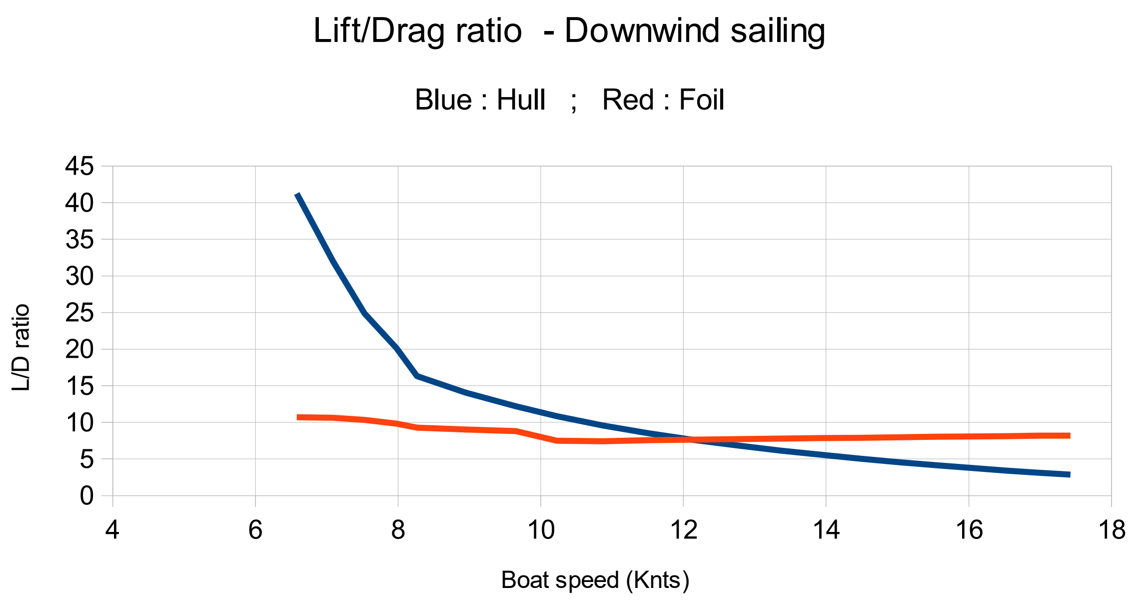
Example at wind speed 20 Knots :





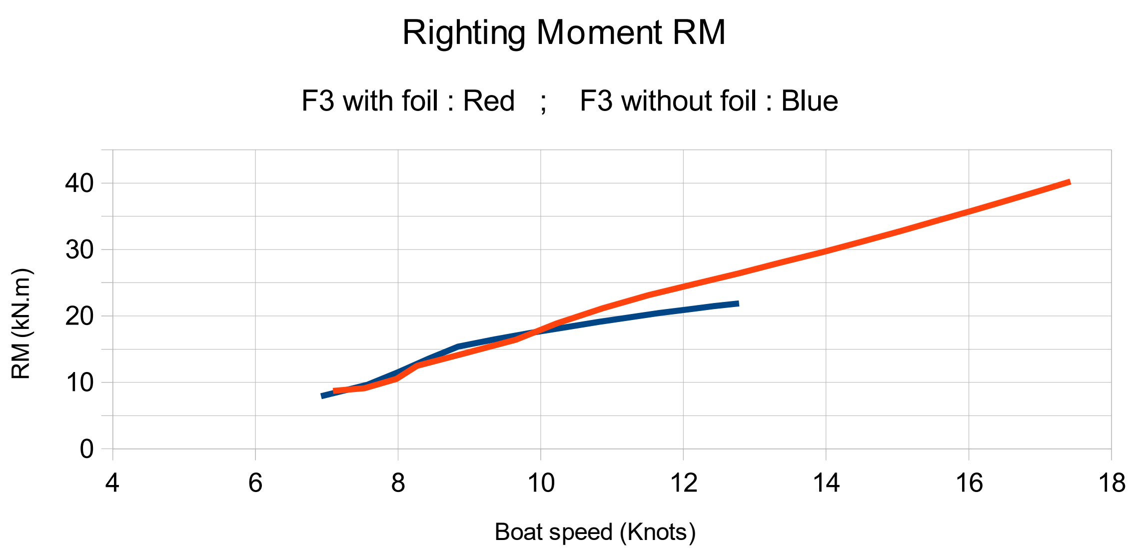
>>> By strong winds (here 20 Knots), it is the confirmation to use the foil maximum lift coefficient.

F3 : Lift/Drag ratio of the Foil and comparison with the one of the « remaining » Hull (i.e. the boat except its foil)



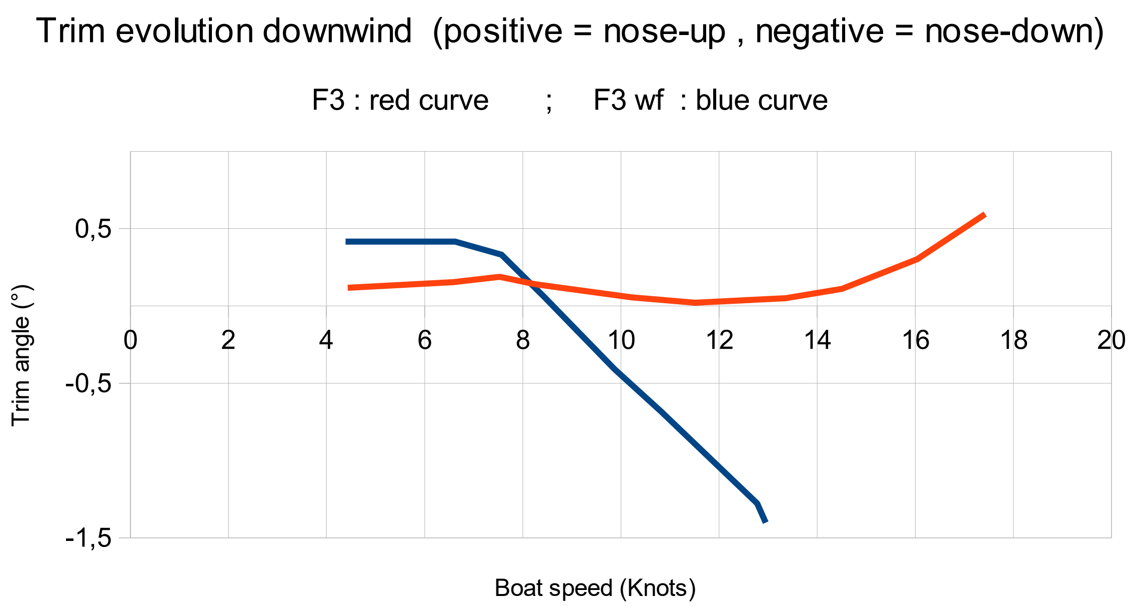
>>> At boat speed > 12 Knots, the Lift/Drag ratio of the Foil becomes higher than the « remaining » hull one, meaning that the foil provides the double advantage of more RM and less drag. ***At boat speed 17 Knots, the Foil L/D is 8,2 and the Hull L/D is 3,1.***
>>> At medium boat speed, 8 to 12 Knots, the Foil L/D is lower than the Hull one in a ratio of 1 to 2, and the Foil advantage can rely only on the extra RM at a cost of more drag.
>>> At lower boat speed, < 8 Knots, we are like in the upwind conditions where the difference between the two L/D ratios is too high (> 2) to expect an advantage from the foil assistance (in terms of speed on calm water, as the foil can have a benefit role in the pitch damping).

Righting moment evolution with boat speed :



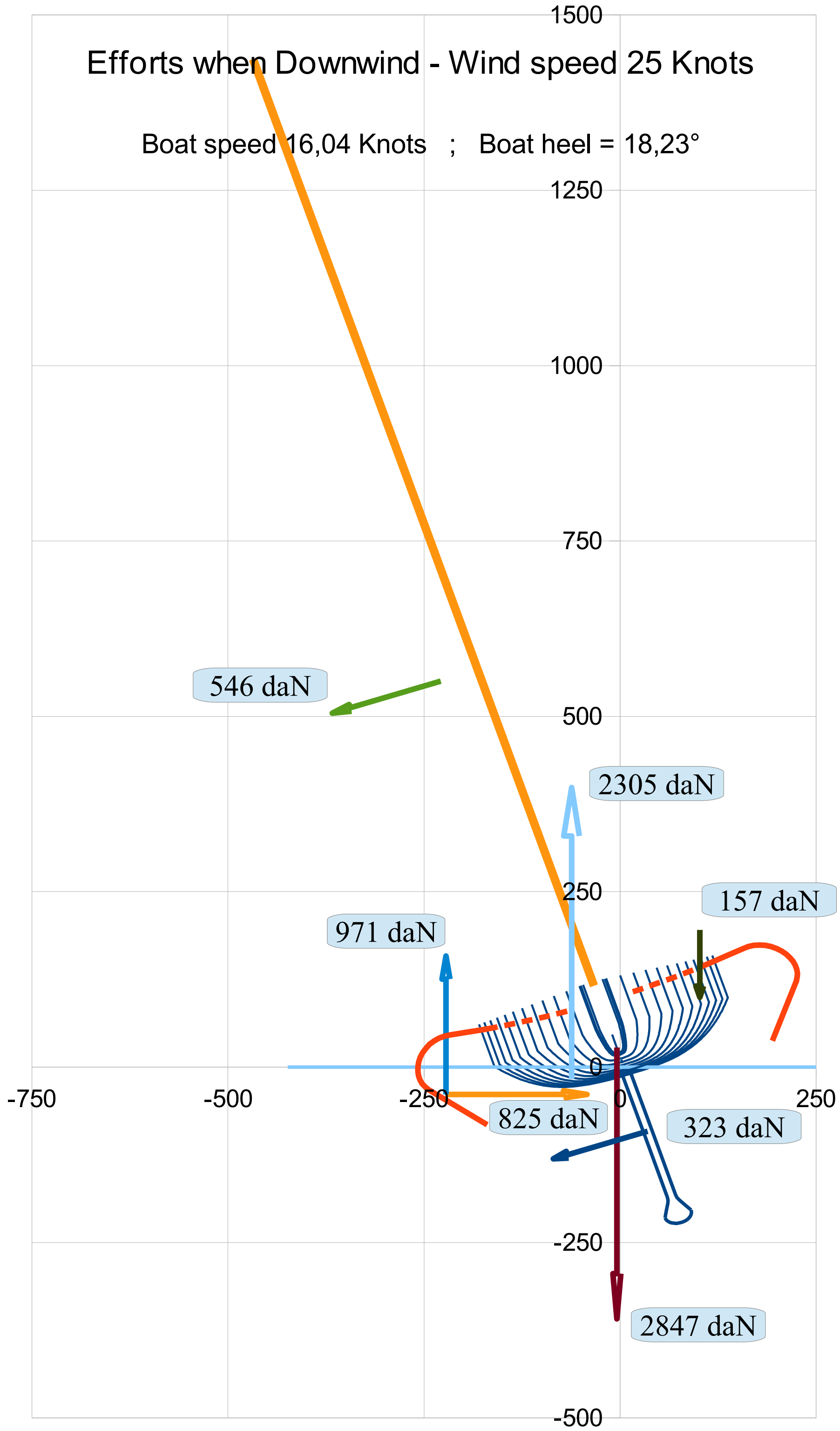
>>> The foil net contribution to the RM is from boat speed 10 Knots. For lower speed, to put the foil equivalent mass in the bulb keel gives a bit more RM.

Trim evolution with boat speed :



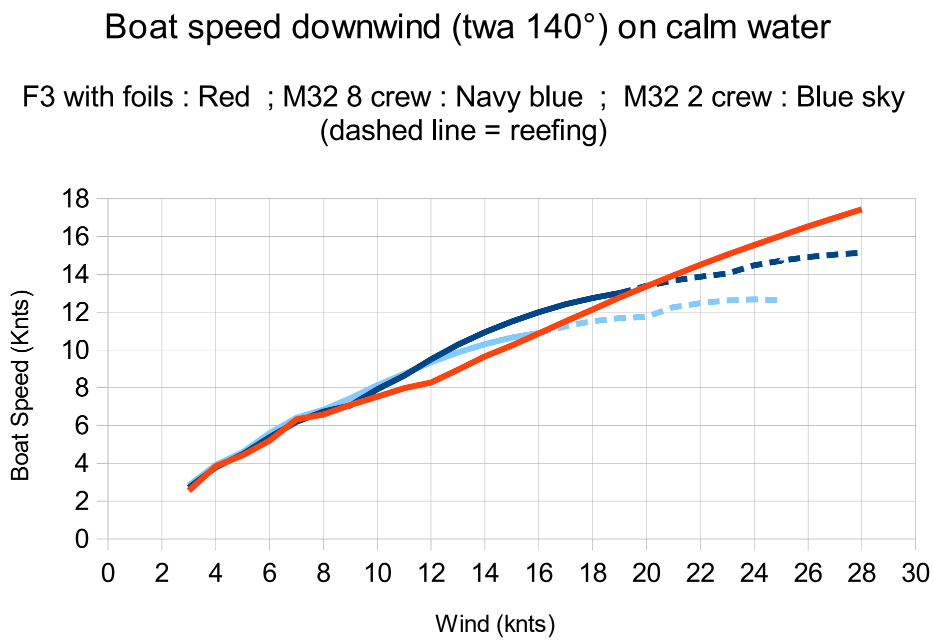
>>> The foil lift is important when sailing downwind, and considering the foil position quite forward in the boat, that has a strong positive effect on the boat trim, preventing the nose-down trend when the boat heels, and contributing to the triggering and the efficiency of the surf mode.

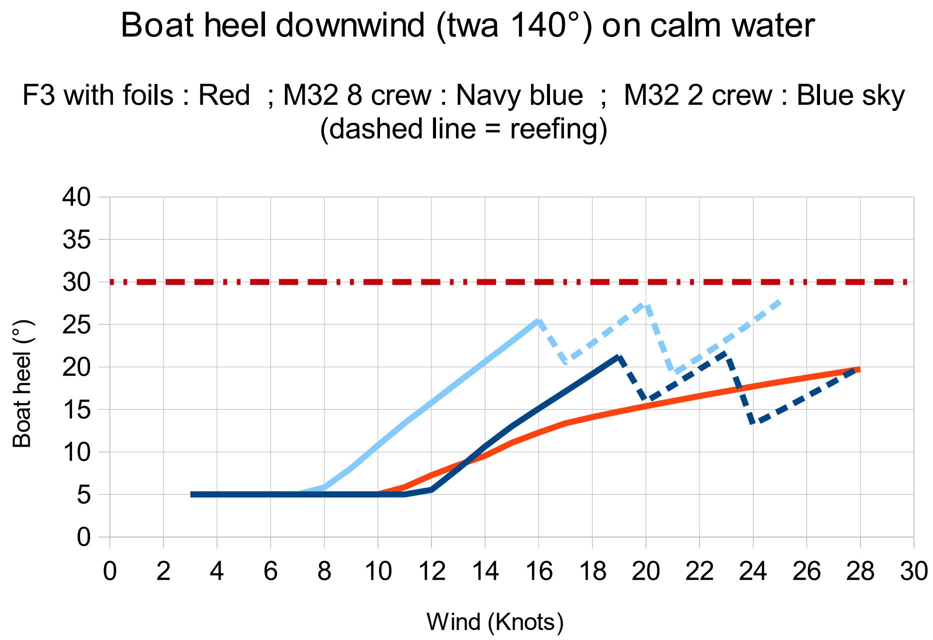
Example of efforts distribution when downwind by wind speed 25 Knots



>>> To note that the foil provides a so powerful lateral force that the keel wing acts reversly for maintaining the equilibrium (i.e. the boat is push windward, the leeway angle is negative).

2.2 Comparison F3 (2 crew) / M32 (8 crew) and M32 (2 crew)





>>> For light winds up to 9 Knots wind speed, speeds are roughly equivalent with a slight advantage for the M32 (2 crew).

>>> For medium, from 9 to 20 Knots wind speed, the M32 (8 crew) shows the greater speed, up to 1,3 knots more when 14 Knots wind : 10,9 knots / 9,6 Knots

>>> For strong winds > 20 Knots, F3 is faster than M32 (8 crew) needing a sail reduction, up to 2,2 Knots more when 28 Knots wind speed : 17,4 knots / 15,2 knots.

>>> F3 can sustain its nominal sail surface up to 28 Knots wind speed, M32 crew should reef from 19 Knots and M32 2 crew from 16 Knots.

Annexes :

Hydrostatics data of F3 in light weight conditions without crew (>> displacement : 2902 kg)

2. Data sum-up and results of hydrostatic and surfaces calculations								
2.1 Hull								
Loa (m)	**9,75**	**Lwl (m)**	**9,40**					
>> ft	31,99		30,84					
B (m)	**3,47**	**at X (% Lwl)**	**15,0**					
>> ft	11,40							
Bwl (m)	**2,52**	**at X (% Lwl)**	**32,0**	> Bwl/B	0,726			
>> ft	8,28				**Freeboards (m) >**	**Aft**	**Midship**	**Fore**
Tc (m)	**0,282**	**at X (%Lwl)**	**43,0**			**0,42**	**0,36**	**1,09**
>> ft	0,93				>> ft	1,38	1,18	3,58
	Displacement at H0 (m3)	**2,71221**	**at Xc (m)**	**4,275**	**Xc (%Lwl)**	**45,48**	**Zc (m)**	**-0,103**
	>> lbs	6129	w. seawater	1025	kg/m3		>> ft	-0,34
Disp at H(cm)	-3,00	2,23206	at Xc (m)	4,315	Xc (%Lwl)	45,90	Zc (m)	-0,091
Disp at H(cm)	3,00	3,22703	at Xc (m)	4,235	Xc (%Lwl)	45,05	Zc (m)	-0,114
Cp (%)	**55,90**							
Sf (m2)	**16,69**	**at Xf (m)**	**4,045**	**Xf (%Lwl)**	**43,03**		>>> Xc – Xf (%Lwl)	2,45
>> ft2	179,63	>> ft	13,27					
	Angle immersed sheer Ii (°)	**31,4**	at section C4 (40% Lwl)					
Sw (m2)	**17,23**	>Sm/D^(2/3)	8,86					
>> ft2	185,47							
Shull (m2)	**40,74**	**at X (m)**	**4,290**	**Z (m)**	**0,182**			
>> ft2	438,49	>> ft	14,07	>> ft	0,60			
Sdeck (m2)	**24,67**	**at X (m)**	**3,794**					
>> ft2	265,53	>> ft	12,45					
2.2 Keel								
Vol. keel (m3)	**0,04779**	**at X (m)**	**4,600**	**X (%Lwl)**	**48,94**	**Z (m)**	**-1,144**	
Mass keel(kg)	**375,15**	>> ft	15,09			>> ft	-3,75	
>> lbs	827							
Vol. Bulb(m3)	**0,05442**	**at X (m)**	**4,247**	**X (%Lwl)**	**45,19**	**Z (m)**	**-2,355**	
Mass bulb(kg)	**617,71**	>> ft	13,94			>> ft	-7,73	
>> lbs	1362							
Draft oa (m)	**2,50**		**Sw (m2)**	**2,66**		**Sxz (m2)**	**0,85**	
>> ft	8,20		>> ft2	28,68		>> ft2	9,14	
LCR (m)	**4,67**	**LCR (%Lwl)**	**49,68**					
>> ft2	50,27	method : keel profile extended to the waterline, LCR at 25% chord and 45% draft oa						
2.3 Rudder(s)								
Number	**2**							
Volume (m3)	**0,01727**	**at X (m)**	**0,051**	**X (%Lwl)**	**0,54**	**Z (m)**	**-0,306**	
Sw (m2)	**1,33**	>> ft	0,17			**Sxz (m2)**	**0,32**	per rudder
>> ft2	14,29					>> ft2	3,43	
2.4 Hull + Keel + Rudder(s)								
	Displacement at H0 (m3)	**2,83170**	**at Xc (m)**	**4,254**	**Xc (%Lwl)**	**45,26**	**Zc (m)**	**-0,165**
	(kg)	**2902**	>> ft	13,96			>> ft	-0,54
	>> lbs	6399						
	Ballast (kg)	**993**	**at Xg (m)**	**4,381**	**Xg (%Lwl)**	**46,60**	**Zg (m)**	**-1,897**
	>> lbs	2189	>> ft	14,37			>> ft	-6,23
	>> % Ballast	34,2						
	Sw (m2)	**21,22**	>Sw/D^(2/3)	10,60	Lwl/D^(1/3)	6,64		
	>> ft2	228,43			M/(Lwl/100)^3	99	tons, feet	

Hydrostatics data of M32 in light weight conditions without crew (>> displacement : 1712 kg)

2. Data sum-up and results of hydrostatic and surfaces calculations

2.1 Hull

Loa (m)	**9,70**	**Lwl (m)**	**9,09**	> Lwl/D^(1/3)	7,82				
>> ft	*31,82*		*29,82*						
B (m)	**3,00**	**at X (% Lwl)**	**34,0**						
>> ft	*9,83*								
Bwl (m)	**2,15**	**at X (% Lwl)**	**39,0**	> Bwl/B	0,716				
>> ft	*7,04*					**Freeboards (m) >**	**Aft**	**Midship**	**Fore**
Tc (m)	**0,181**	**at X (%Lwl)**	**50,0**				**0,68**	**0,78**	**0,92**
>> ft	*0,59*					*>> ft*	*2,23*	*2,56*	*3,02*
Displacement at H0 (m3)	**1,57055**	**at Xc (m)**	**4,232**	**Xc (%Lwl)**	**46,56**			**Zc (m)**	**-0,07**
>> lbs	*3549*	*w. seawater*	*1025*	*kg/m3*				*>> ft*	*-0,23*
Displacement at H-3cm (m3)	1,17752	at Xc (m)	4,299	Xc (%Lwl)	47,30			Zc (m)	-0,06
Displacement at H+3cm (m3)	1,99671	at Xc (m)	4,169	Xc (%Lwl)	45,86			Zc (m)	-0,08
Cp (%)	**57,20**								
Sf (m2)	**13,74**	**at Xf (m)**	**3,967**	**Xf (%Lwl)**	**43,64**			>>> Xc – Xf (%Lwl)	2,92
>> ft2	*147,87*	*>> ft*	*13,01*						
Angle immersed sheer li (°)	**27,5**	at section C4 (40% Lwl)							
Sw (m2)	**14,03**	>Sm/D^(2/3)	10,39						
>> ft2	*151,04*								
Shull (m2)	**32,08**	**at X (m)**	**414,78**	**Z (m)**	**0,14**				
>> ft2	*345,34*	*>> ft*	*1360,83*	*>> ft*	*0,46*				
Sdeck (m2)	**21,24**	**at X (m)**	**375,51**						
>> ft2	*228,59*	*>> ft*	*1231,99*						

2.2 Keel

Vol. keel (m3)	**0,06028**	**at X (m)**	**4,436**	**X (%Lwl)**	**48,80**	**Z (m)**	**-0,99**
Mass keel(kg)	**440,06**	*>> ft*	*14,55*			*>> ft*	*-3,24*
>> lbs	*970*						
Vol. Bulb(m3)	**0,02948**	**at X (m)**	**4,246**	**X (%Lwl)**	**46,71**	**Z (m)**	**-2,00**
Mass bulb(kg)	**334,65**	*>> ft*	*13,93*			*>> ft*	*-6,56*
>> lbs	*738*						
Draft oa (m)	**2,13**			**Sw (m2)**	**2,90**	**Sxz (m2)**	**1,17**
>> ft	*6,99*			*>> ft2*	*31,27*	*>> ft2*	*12,55*
LCR (m)	**4,54**	method : keel profile extended to the waterline, 25% c at 45% draft oa					
>> ft2	*48,81*						

2.3 Rudder(s)

Number	**1**							
Volume (m3)	**0,00985**	**at X (m)**	**-0,100**	**X (%Lwl)**	**-1,10**	**Z (m)**	**-0,60**	
Sw (m2)	**0,86**	*>> ft*	*-0,33*			**Sxz (m2)**	**0,41**	per rudder
>> ft2	*9,25*					*>> ft2*	*4,45*	

2.4 Hull + Keel + Rudder(s)

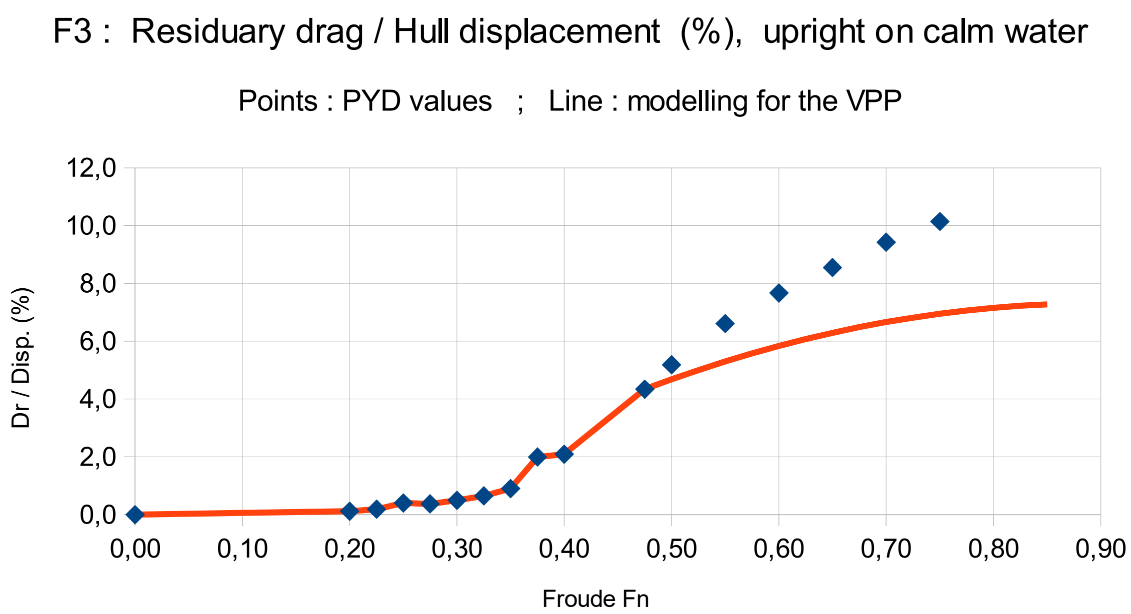
Displacement at H0 (m3)	**1,67017**	**at Xc (m)**	**4,214**	**Xc (%Lwl)**	**46,36**	**Zc (m)**	**-0,14**
(kg)	**1712**	*>> ft*	*13,83*			*>> ft*	*-0,46*
>> lbs	*3774*						
Ballast (kg)	**775**	**at Xg (m)**	**4,354**	**Xg (%Lwl)**	**47,90**	**Zg (m)**	**-1,42**
>> lbs	*1708*	*>> ft*	*14,29*			*>> ft*	*-4,67*
>> % Ballast	45,3						
Sw (m2)	**17,80**	>Sw/D^(2/3)	12,64	Lwl/D^(1/3)	7,66		
>> ft2	*191,56*			*M/(Lwl/100)^3*	*65*	*tons, feet*	

Residuary drag of the hull :

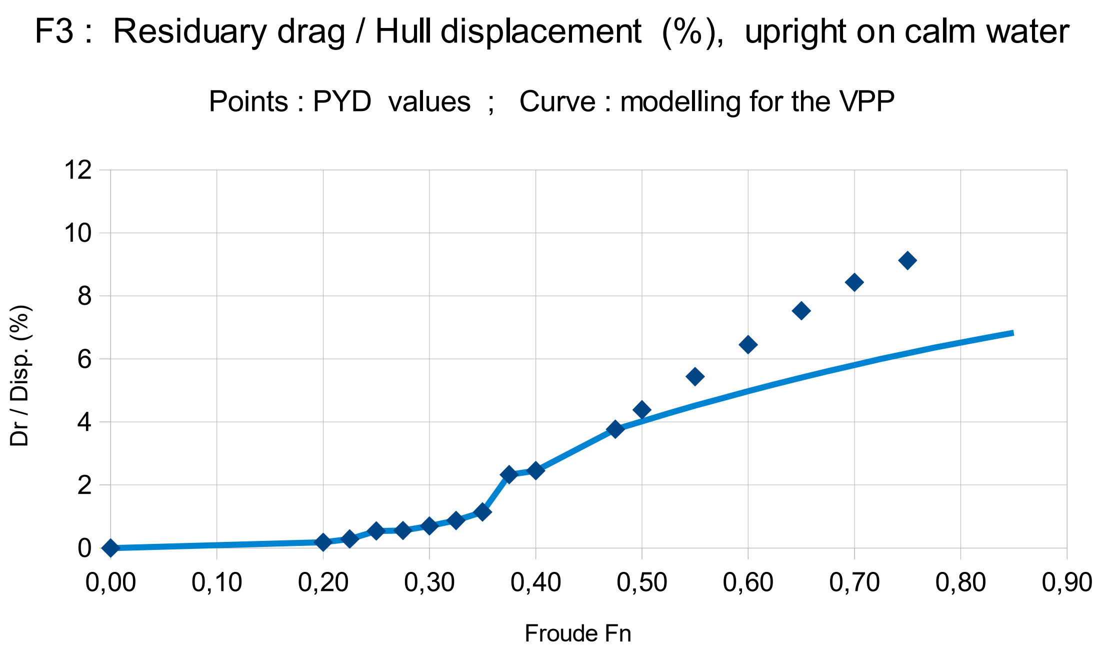
The drag components are the direct application of Larsson-Eliasson method and formulations as described in their book « Principles of Yacht Design » Second edition 2000.

The only change is for the residuary drag Dr in the Fn range 0,475 – 0,75 to take into account the surfing specific ability show by these boats : the ratio Dr / Hull Displacement is mitigated accordingly, and of course in the same proportion for both the F3 model and the M32 one to not alter the performance comparison. Here are the values used :

For F3 :

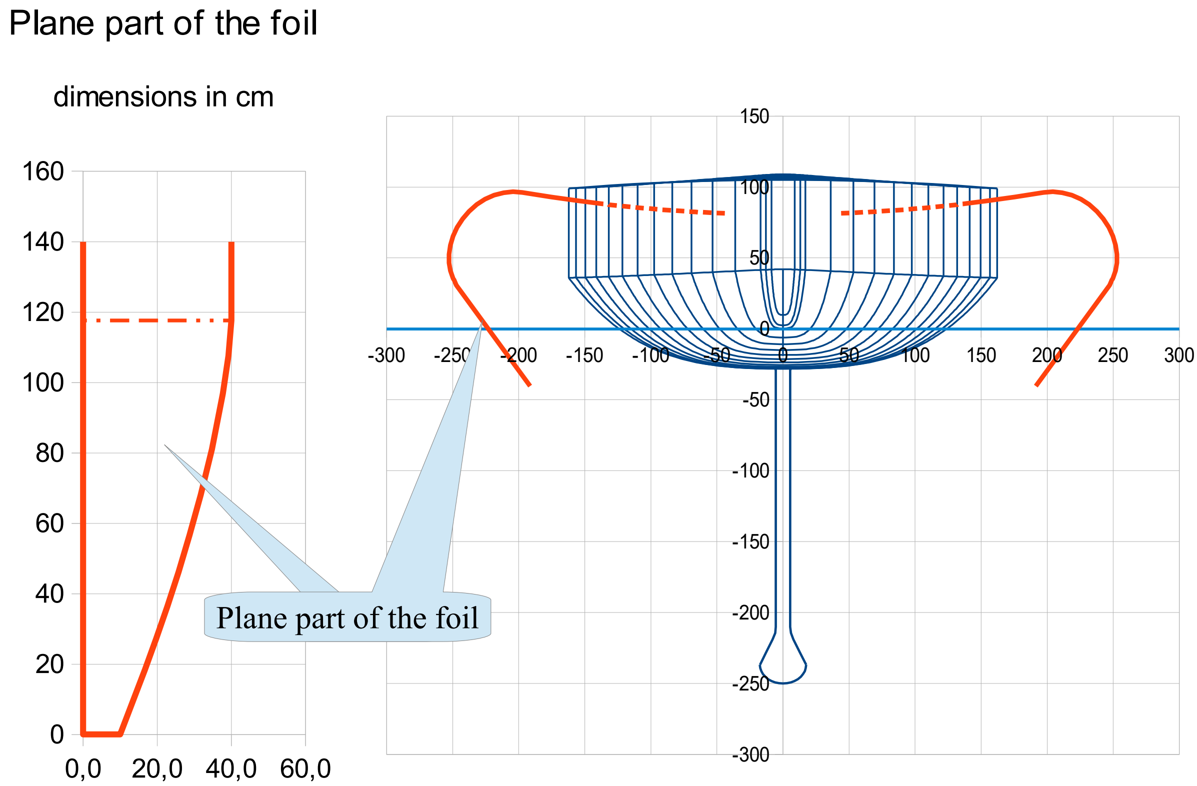


For M32 :



The Foil modelling :

The foil includes a plane part, tilted at about 38° / vertical, which provides the main part of the lift.



The lift surface is computed at each VPP iteration due to the boat attitude (heel angle, elevation height, trim). For low heel angle (< ~ 7°), the winward foil tip can be still in the water.

The foil curved part, when also immersed due to the boat heel, is taken into account for the lift computation. From the whole geometry of the foil so immersed and acting for the lift, we can derive an effective Aspect Ratio.

The Foil rake can be adjusted. In the real conditions, the upstream flow incidence on the foil is complex to evaluate. For simplification, instead of consider the foil rake angle as the parameter for the search of an optimum, we consider that a range of CL 2D from 0 to 1,2 is available thanks to this degree of freedom (a typical range for a profile like a Naca 2410), from which, using the above Aspect Ratio and the lifting line theory, lift coefficient « CL 3D » and induced drag coefficient « CD induced » are computed.