Residuary drag estimation for a sailing catamaran

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V2 :

- Some minor corrections of the V1 version
- Two approaches A and B for the slender monohull Dr/Mg versus Froude Fn :
  - A) with Lw/Bw as the main parameter + a correction for Bw/Tc
  - B) with Lw/D^1/3 as unique parameter, providing that the Lw/Bw and the Bw/Tc remain in their respective range, 7 to 15 and 1,5 to 2,5
- The numerical examples are given with the two approaches

V3 :

- The approach B with Lw/D^1/3 as unique parameter is completed with some other test results (Series 64, SSPA, NPL) as reported by Oossanen in : **https://www.oossanen.nl/beheer/wp-content/uploads/2013/02/petervanoossanen_-_resistance_prediction_of_small_high-speed_displacement_vessels.pdf**
- a new Fib. 1B is proposed and the numerical examples are updated accordingly

Introduction

From the towing tank tests of a serie of slender hull models sharing the same block coefficient (Cb ~0,4), tested both in a monohull and in a catamaran configurations, one can propose this exploitation of the results oriented to the evaluation of the residuary drag component Dr, for :

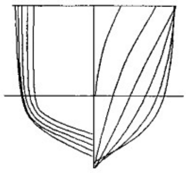
- a slender monohull
- the upright catamaran : the motoryacht cata issue, with 2 hulls identical in the water
- the heeled catamaran : the sailing cata issue, with a leeward hull and a windward hull

Summary

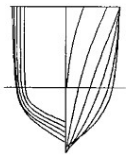
1. The towing tank tests investigated

A serie of models were tested in the University Southampton towing tank and reported here below by A.F Molland / University of Southampton and Pat Couser / Bentley systems in january 1994 : 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

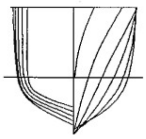
The tested models :



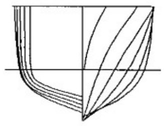
Model: 3b



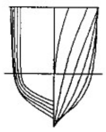
Model: 4a



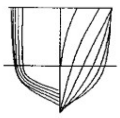
Model: 4b



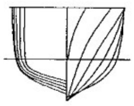
Model: 4c



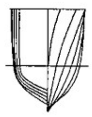
Model: 5a



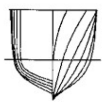
Model: 5b



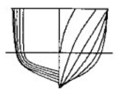
Model: 5c



Model: 6a



Model: 6b



Model: 6c

Model	L (m)	L/B	B/T	L/D^1/3	Cb	Cp	Cm	Sw (m2)	LCB (%Lwl)	>> D(m3)	>> D (kg)
3b	1,6	7,0	2,0	6,27	0,397	0,693	0,565	0,434	-6,4	0,016617	16,62
4a	1,6	10,4	1,5	7,40	0,397	0,693	0,565	0,348	-6,4	0,010108	10,11
4b	1,6	9,0	2,0	7,41	0,397	0,693	0,565	0,338	-6,4	0,010067	10,07
4c	1,6	8,0	2,5	7,39	0,397	0,693	0,565	0,34	-6,4	0,010149	10,15
5a	1,6	12,8	1,5	8,51	0,397	0,693	0,565	0,282	-6,4	0,006646	6,65
5b	1,6	11,0	2,0	8,50	0,397	0,693	0,565	0,276	-6,4	0,006670	6,67
5c	1,6	9,0	2,5	8,49	0,397	0,693	0,565	0,277	-6,4	0,006693	6,69
6a	1,6	15,1	1,5	9,50	0,397	0,693	0,565	0,24	-6,4	0,004777	4,78
6b	1,6	13,1	2,0	9,50	0,397	0,693	0,565	0,233	-6,4	0,004777	4,78
6c	1,6	11,7	2,5	9,50	0,397	0,693	0,565	0,234	-6,4	0,004777	4,78

In the paper, the residuary drag is extracted from the tests results and given for the monohull configuration (Fig. 32 a to 32 d), as for the catamaran one with various S/L (Fig. 33 to 46d), through the resistance coefficient Cr, applied to ½ ρ A u2, in function of Froude Fn. As A (the static wetted surface), u (the speed, known from the Froude number and the lenght L) and the model mass M (known from L/D^1/3 and M = D ρ) , it is possible to convert these curves in the more appropriated adimensional form for such residuary (mostly wave) drag Dr, i.e. Dr/Mg (%) in function of Fn, so showing its independance to Reynolds.

Another point is the parameters used to graduated the various curves in the paper, in apparence they are 3 : Lwl/Bwl, Bwl/Tc, Lwl/D^1/3. But actually, all the models sharing the same block coefficient Cb (= 0,397), when 2 parameters are given, the third one Lwl/D^1/3 is fixed :

When Lw/Bw and Bw/Tc are fixed >>>

$$Lwl/D^{1/3} = [(Bwl/Tc)/Cb]^{1/3} \; (Lwl/Bwl)^{2/3}$$

When Lw/Bw and Lw/D^1/3 are fixed >>>

$$(Bw/Tc) = Cb \; (Lw/D^{1/3})^3 / (Lw/Bw)^2$$

So the curves presentation can be graduated stating that Cb is common (0,397) and using at max 2 of the 3 ratios for the curves graduation.

For the catamaran configuration, the transversal space S between the 2 hulls axis is introduced, and the ratio S/Lwl is used for the results presentation.

2. The Residuary drag estimation of a slender monohull

2.1 The Lwl/Bwl influence

At first, to demonstrate the approach, here is the Fig.32a of the paper (Residuary drag Dr of the models 3b, 4b, 5b, 6b **at constant Bwl/Tc = 2,0**) and its conversion in curves Dr/Mg (%) in function of Fn :

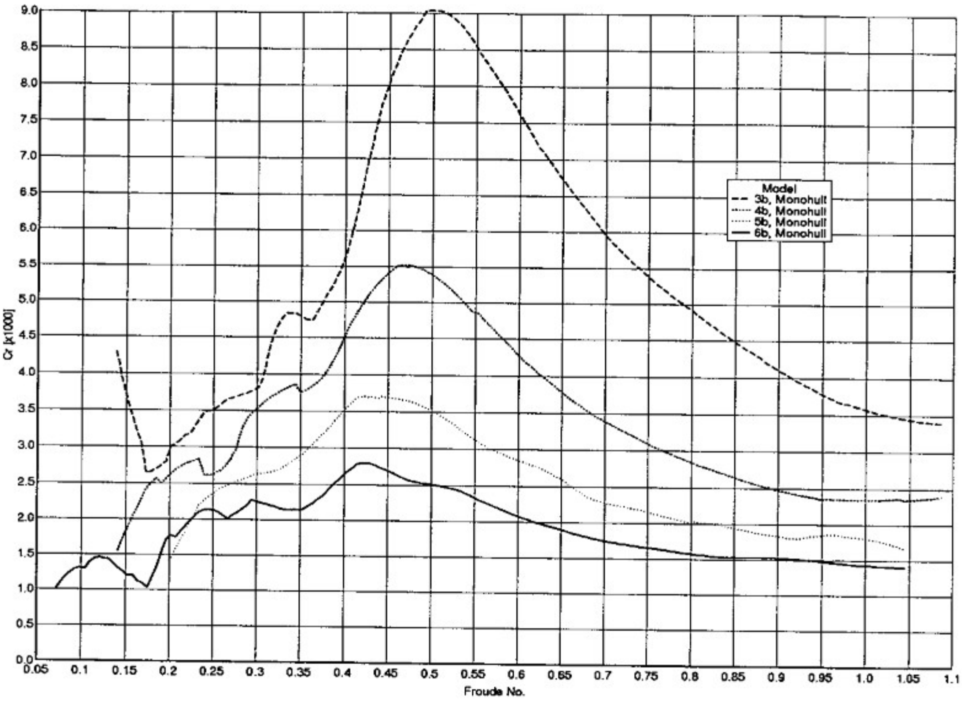
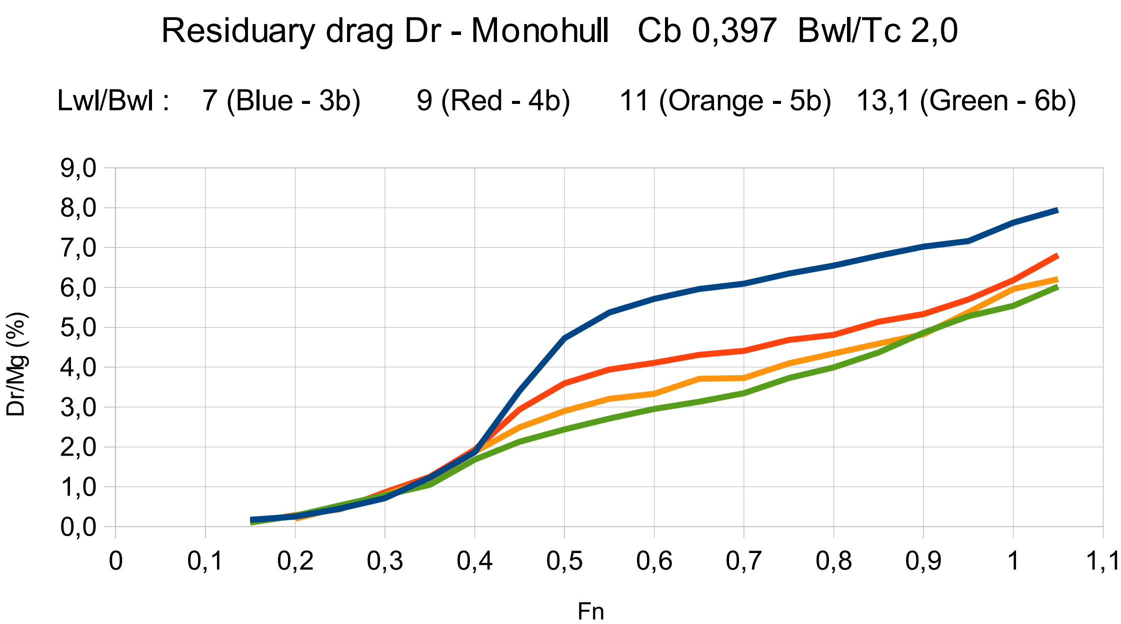
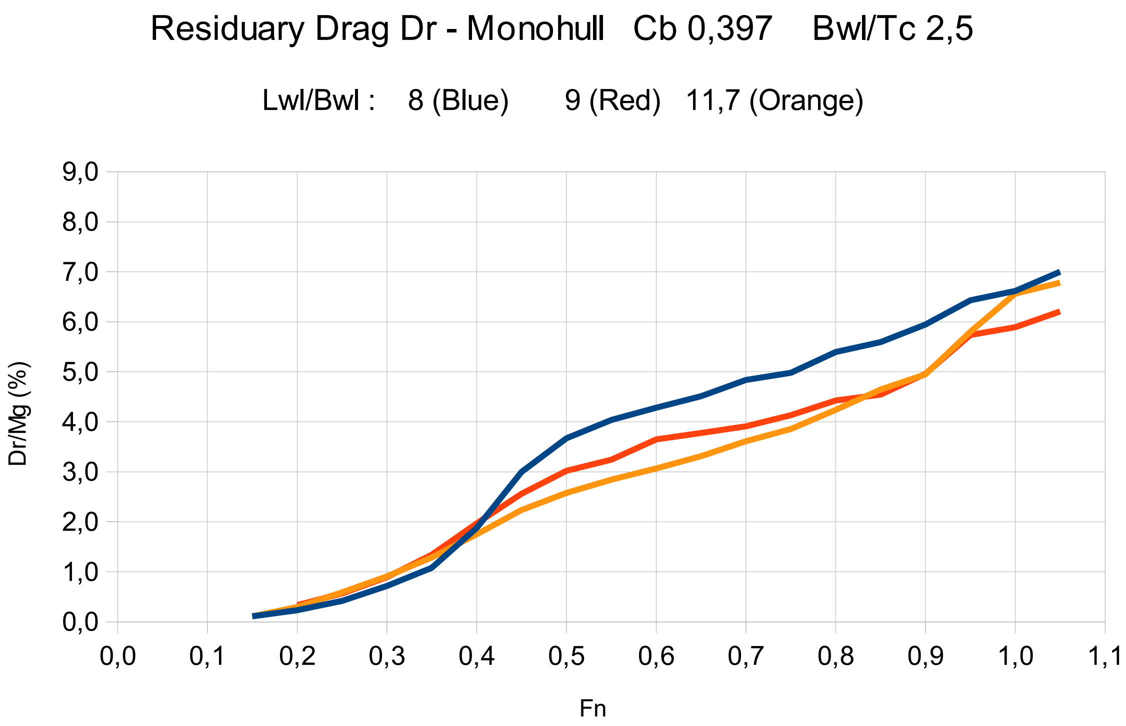


Fig 32a. Residuary Resistance: Models: 3b,4b,5b,6b (Monohull)

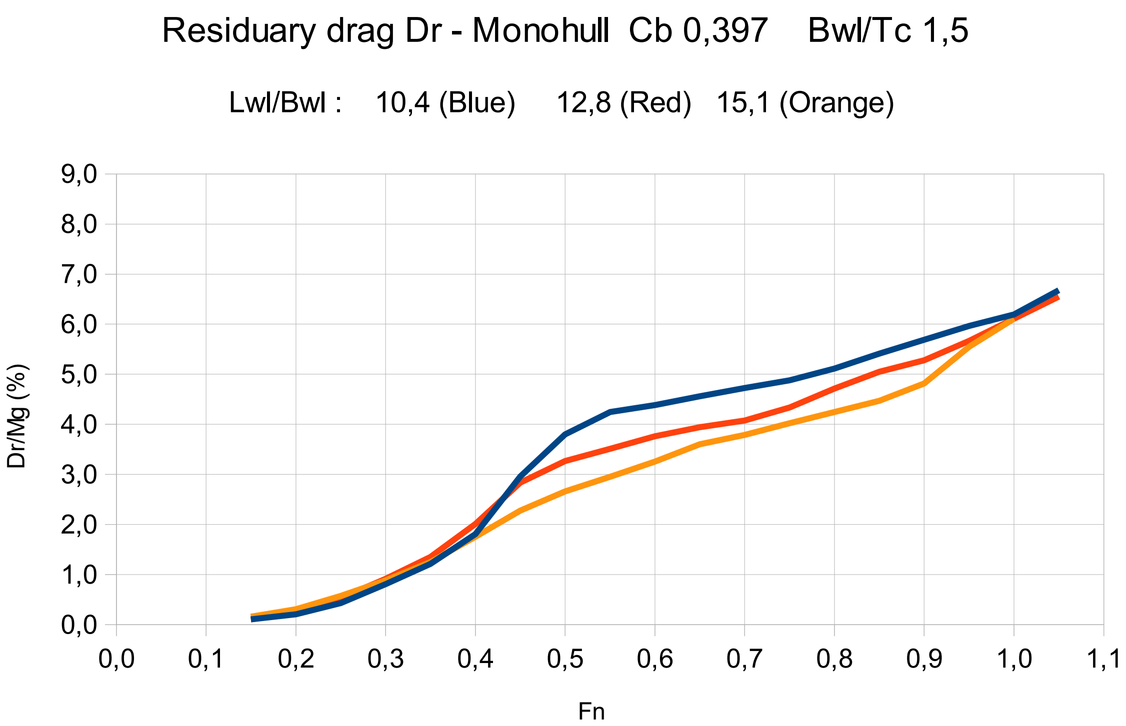


>>> One can see how different the curves appear and the conclusions that can be drawn

Results with models 4c, 5c , 6c , sharing Cb = 0,397 and **Bwl/Tc = 2,5** :
(built from Fig. 32b, 32c and 32d of the paper)



Results with models 4a, 5a , 6a , sharing Cb = 0,397 and **Bwl/Tc = 1,5** :
(built from Fig. 32b, 32c and 32d of the paper)



Comments on these 3 curves for the 3 different Bwl/Tc :

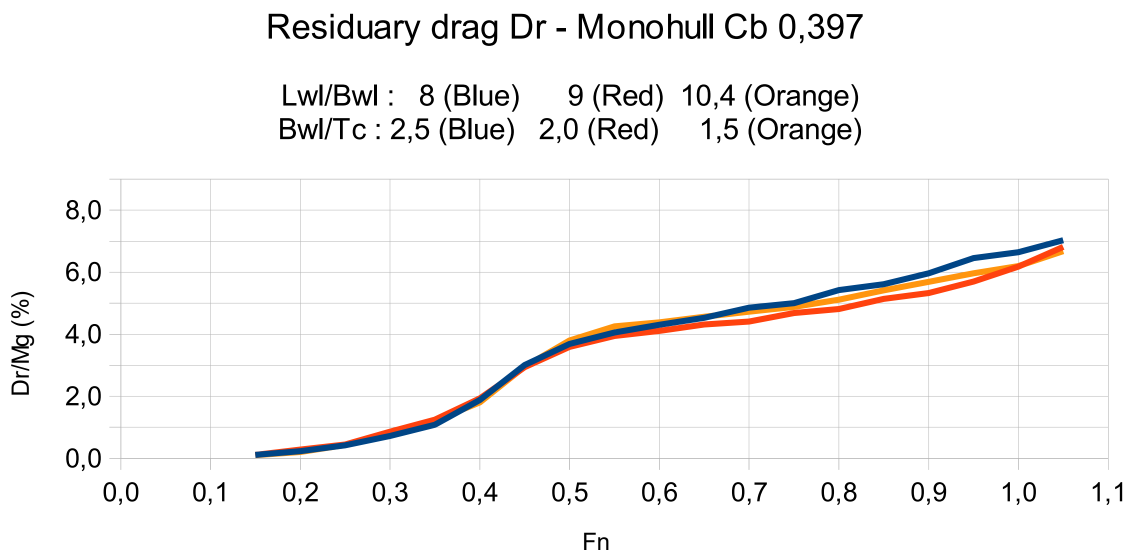
- For Froude < 0,15, Dr is negligeable
- For Froude 0,15 to 0,40 : no clear difference due to the ratio Lwl/Bwl
- For Froude 0,40 to 0,95 : there is a significant graduation of the drag force in the expected order, i.e. the residuary drag decreases when the Lwl/Bwl ratio increases.
- At Froude 0,95 to 1,05 the curves tends to converge to the same drag values.

>>> it seems relevant to aim a Lwl/Bwl > 9 at least to moderate the residuary drag component, an usual recommendation for catamaran hulls

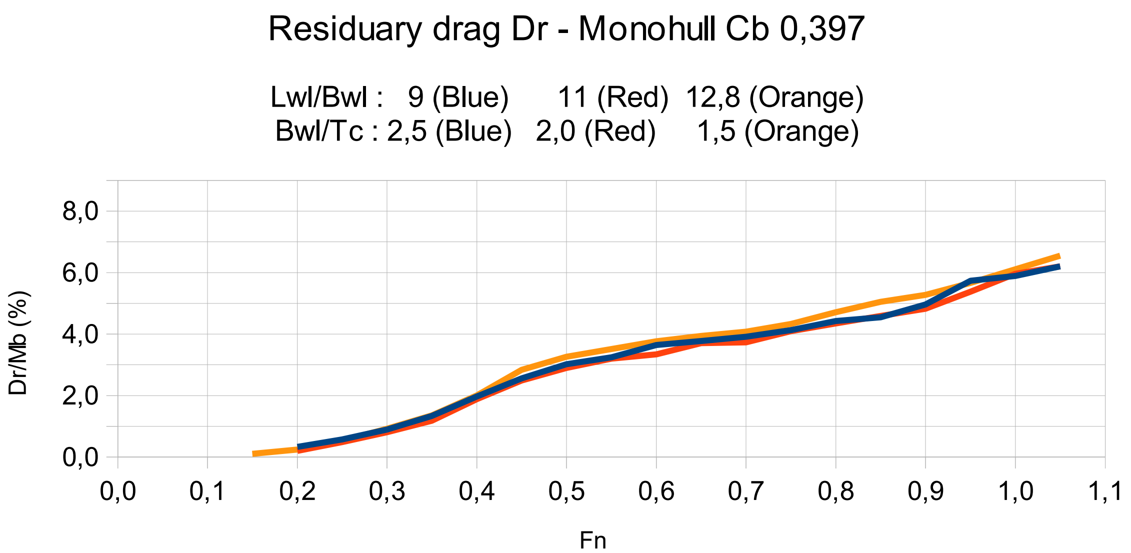
2.2 The Bwl/Tc influence

To show the influence of Bwl/Tc, the paper propose the Fig. 32b, 32c and 32d but they are not at same Lwl/Bwl which prevent to draw consistent conclusions on the Bwl/Tc influence >>>

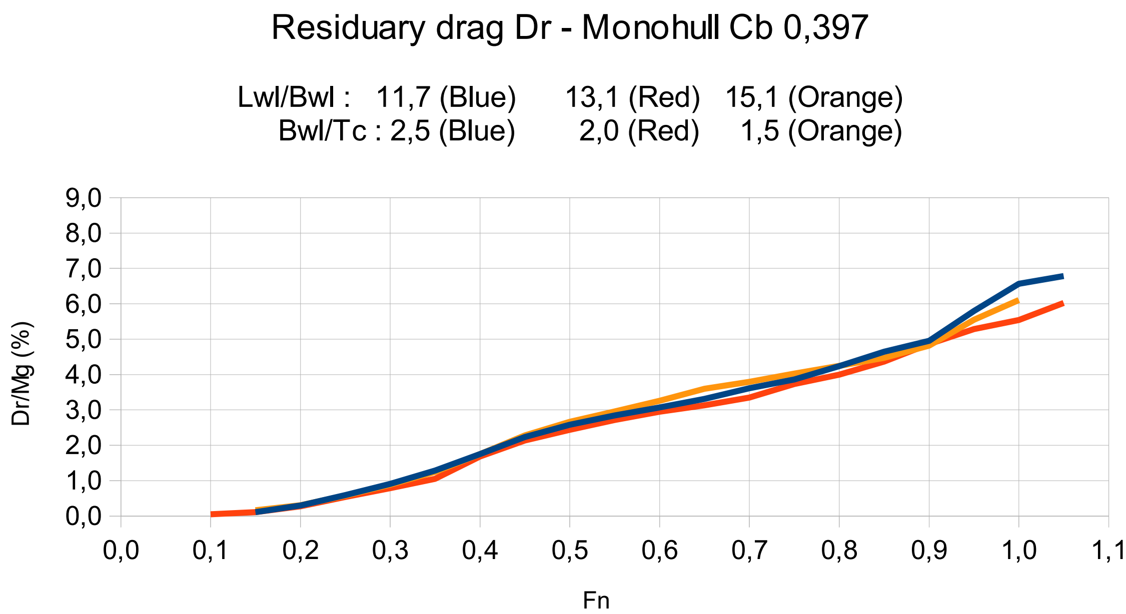
Converted results directly from Fig. 32b with models 4a, 4b , 4c :



Converted results directly from Fig. 32c with models 5a, 5b , 5c :



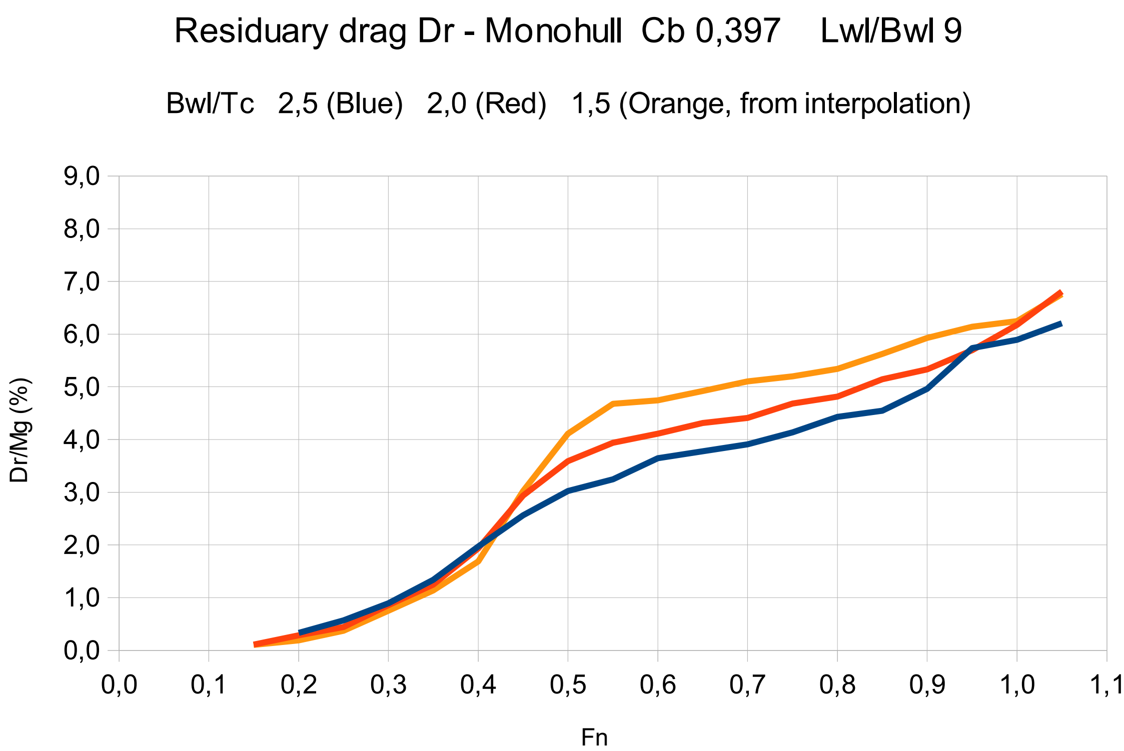
Converted results directly from Fig. 32c with models 6a, 6b , 6c :



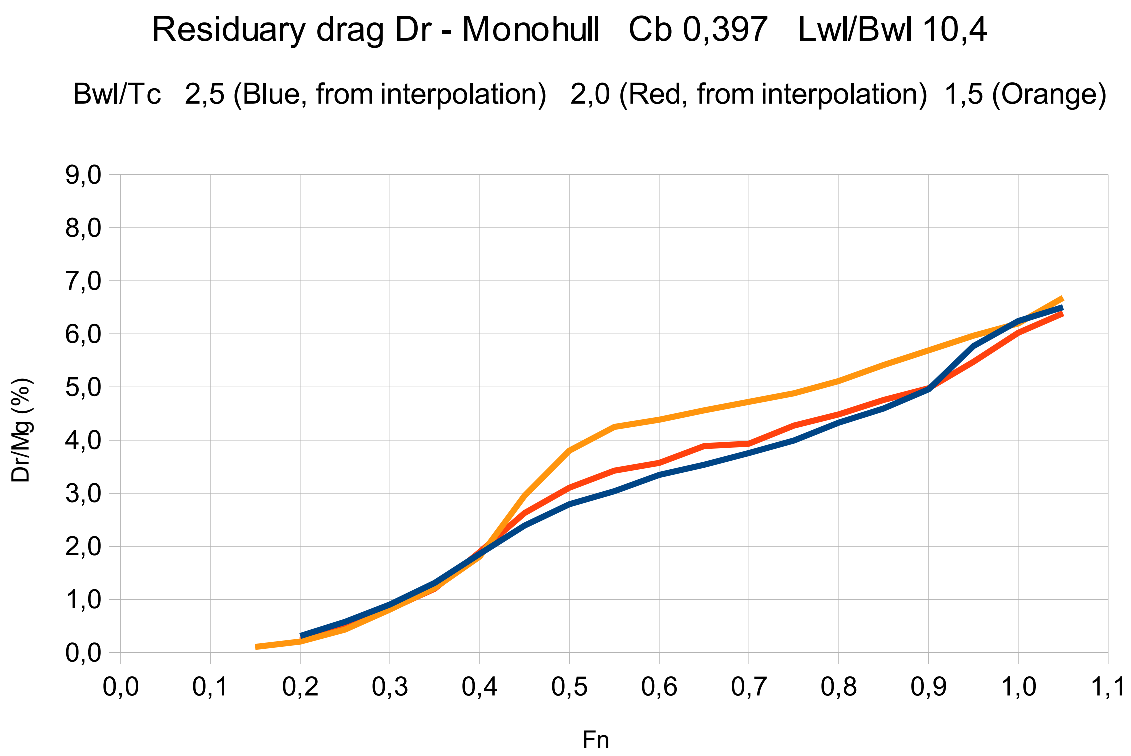
Comments : no apparent differrence but as expected, we cannot draw conclusions on Bwl/tc influence from these figures as the Lwl/Bwl are also variable : e.g. on the figure above how to compare Bwl/Tc 2,5 and 1,5 when associated with Lwl/Bwl with respectively 11,7 and 15,1 ?

>>> So another presentation of the same results is necessary with constant Lwl/Bwl, and it is proposed through some linear interpolation computed from the available data, as close as possible to the real results in order to not loose in consistence and accuracy. That leads to the figures here below, done with 5 different Lwl/Bwl to be sure of the method stability

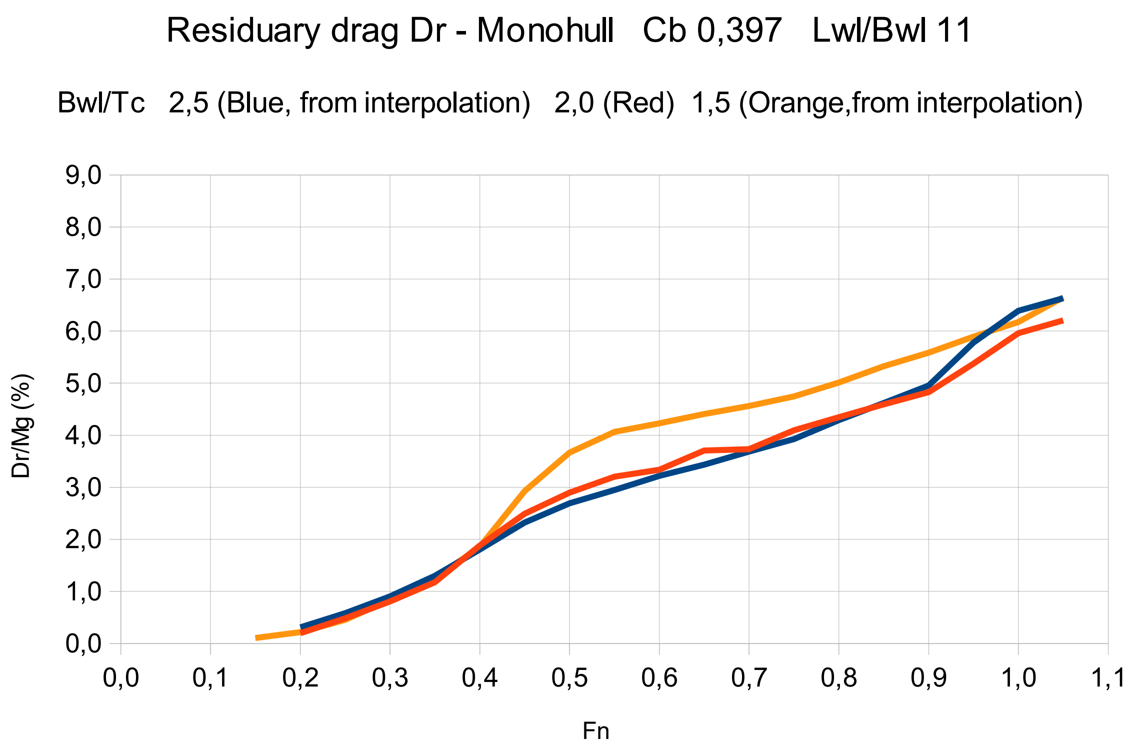
Bwl/Tc influence at Lwl/Bwl = 9



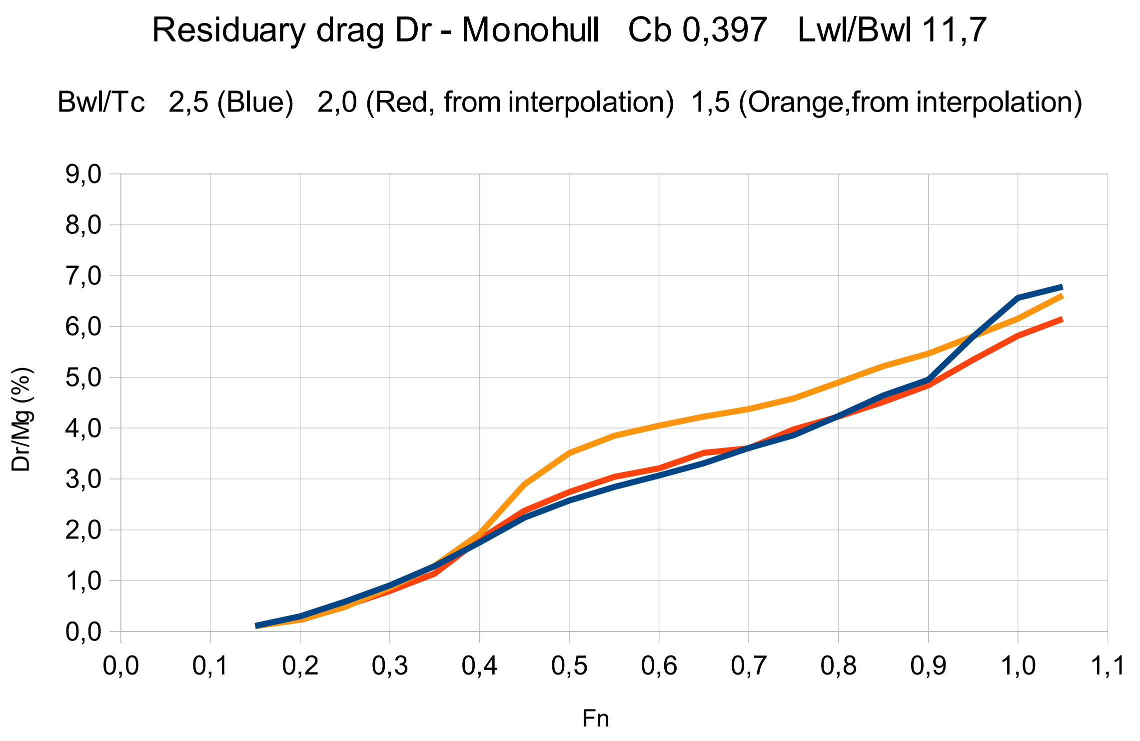
Bwl/Tc influence at Lwl/Bwl = 10,4



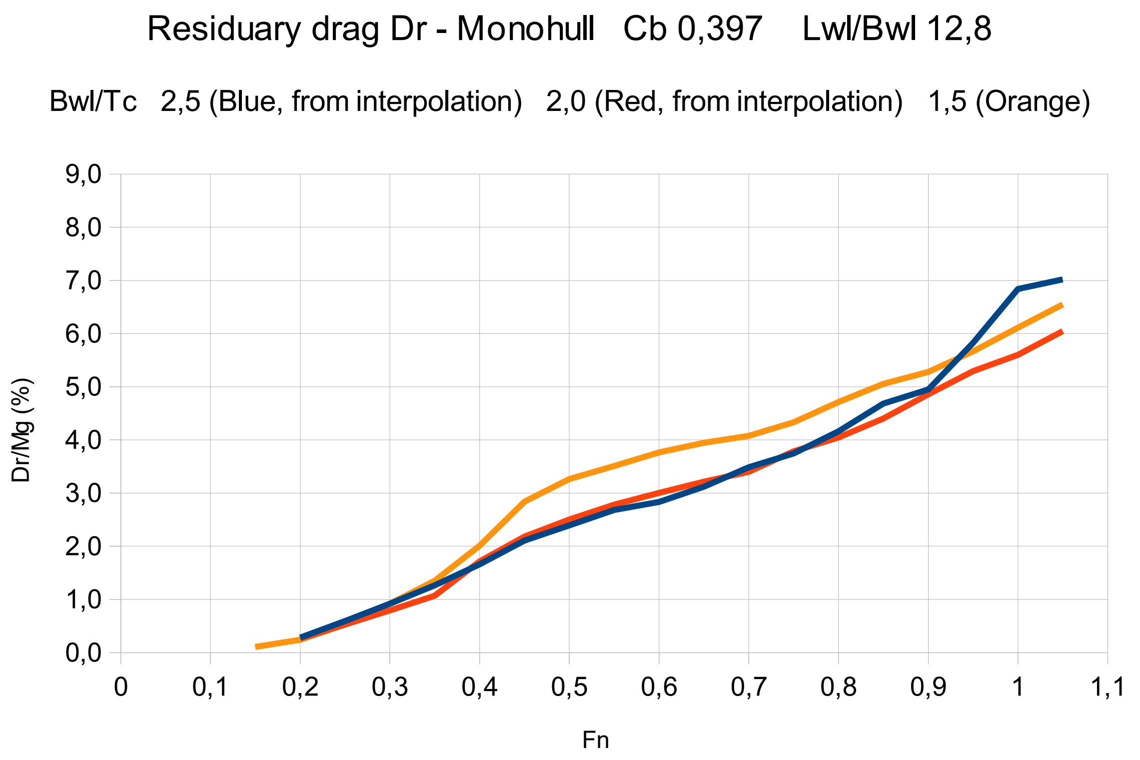
Bwl/Tc influence at Lwl/Bwl = 11



Bwl/Tc influence at Lwl/Bwl = 11,7



Bwl/Tc influence at Lwl/Bwl = 12,8



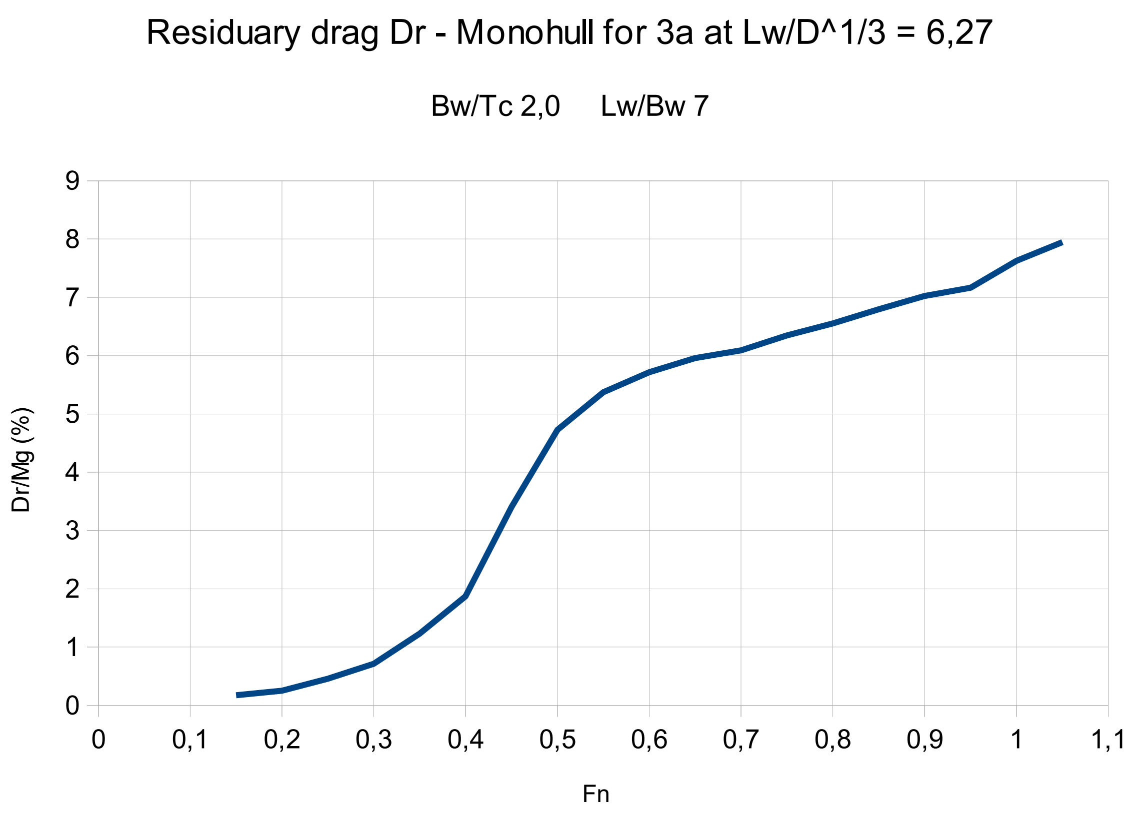
Comments :

- These curves better show the influence of the Bwl/Tc influence, and with consistence : the trends show similarities for each of the 5 cases.
- The conclusions for Froude < 0,4 and for 0,95 to 1,05 are the same as for the previous comments on Lwl/Bwl influence :
  - For Froude < 0,15, Dr is negligeable
  - For Froude 0,15 to 0,40 : no significant difference
  - At Froude 0,95 to 1,05 the curves tends to converge to the same drag values.
- For Froude 0,40 to 0,95 : the graduation of the drag force shows that Bwl/Tc at 1,5 gives significantly more residuary drag. The drag difference for Bwl/Tc between 2,0 and 2,5 is smaller, except at Lwl/Bwl = 9 where the Bwl/Tc = 2,5 shows a slight advantage.
  >>> in this range of Froude (0,4 to 0,95), a correction factor seems relevant to take into account when Bwl/Tc ≠ 2

2.3 The Lw/D^1/3 influence

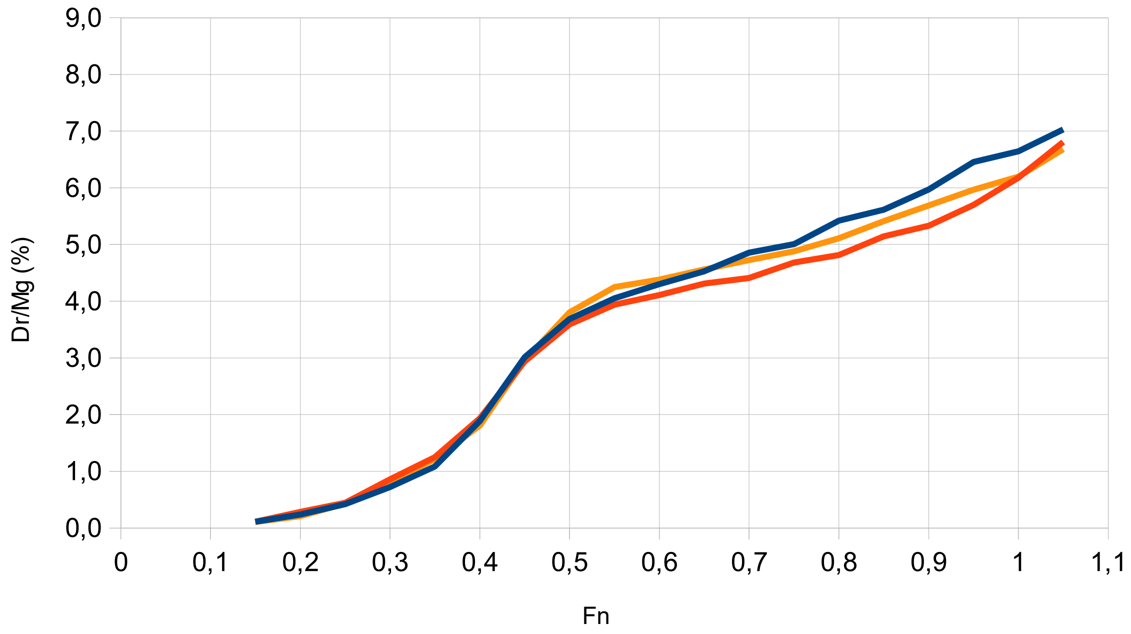
We first show the models results sharing the same Lw/D^1/3 :

Lw/D^1/3 = 6,27 >>> model 3a
Lw/D^1/3 = 7,4 >>> model 4a, 4b, 4c
Lw/D^1/3 = 8,5 >>> model 5a, 5b, 5c
Lw/D^1/3 = 9,5 >>> model 6a, 6b, 6c



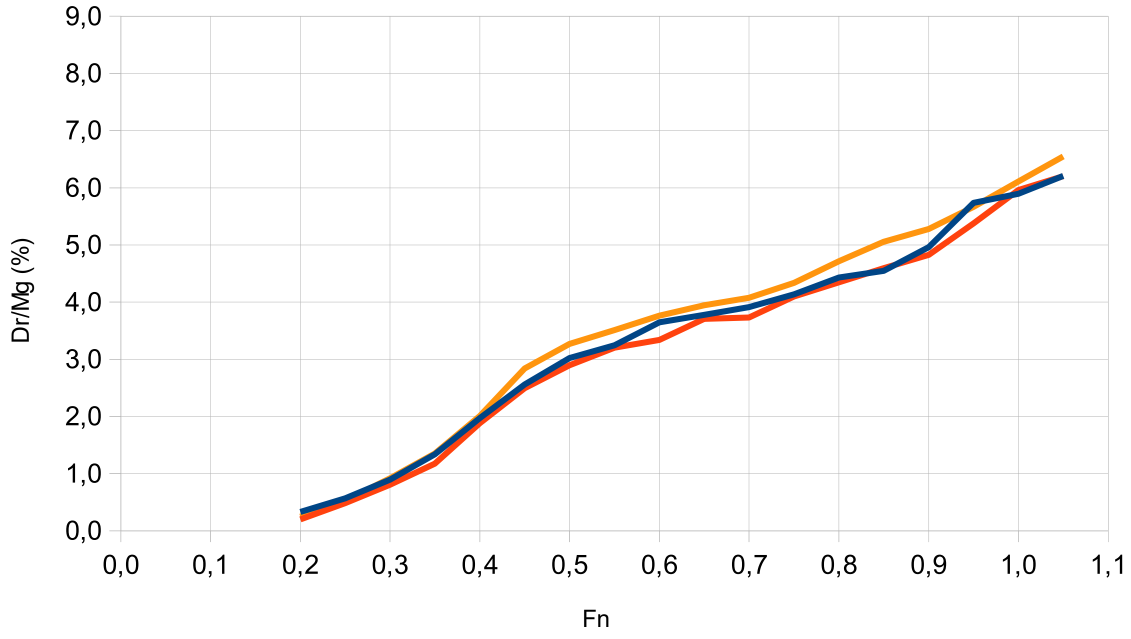
Residuary drag - Monohull 4a, 4b, 4c at constant L/D^1/3 = 7,4

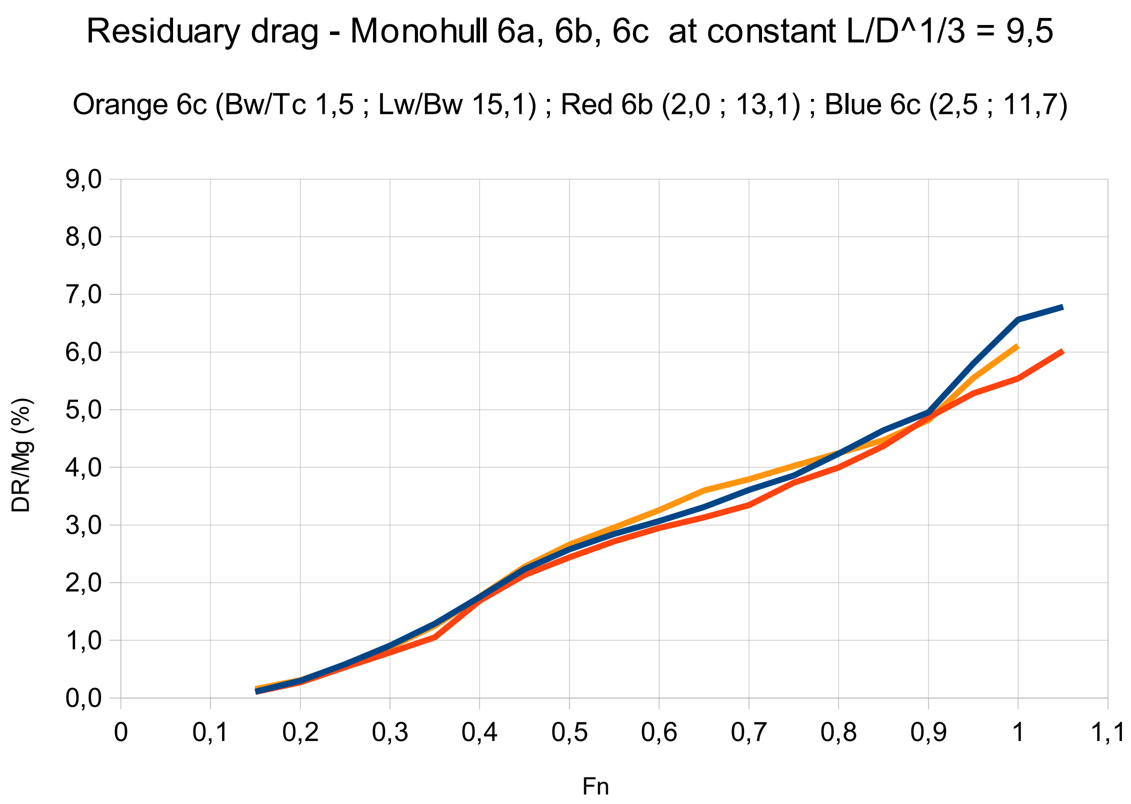
Orange 4a (Bw/Tc 1,5 ; Lw/Bw 10,4) ; Red 4b (2,0 ; 9) ; Blue 4c (2,5 ; 8)



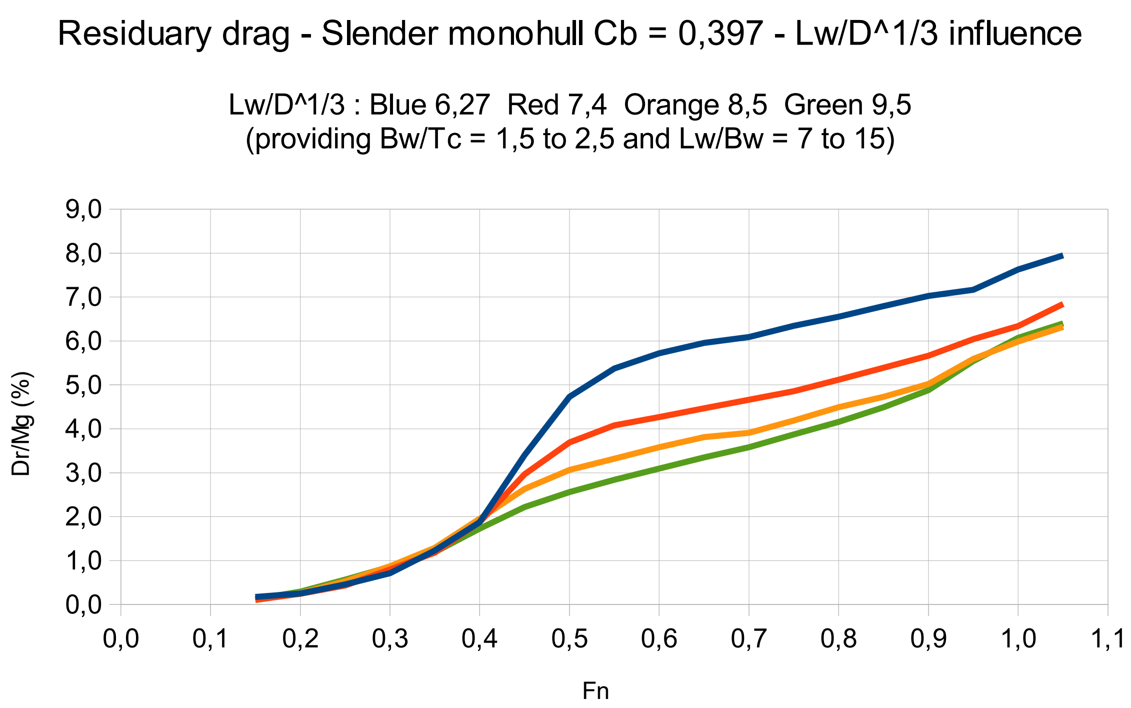
Residuary drag - Monohull 5a, 5b, 5c at constant L/D^1/3 = 8,5

Orange 5a (Bw/Tc 1,5 ; Lw/Bw 12,8) ; Red 5b (2,0 ; 11) ; Blue 5c (2,5 ; 9)





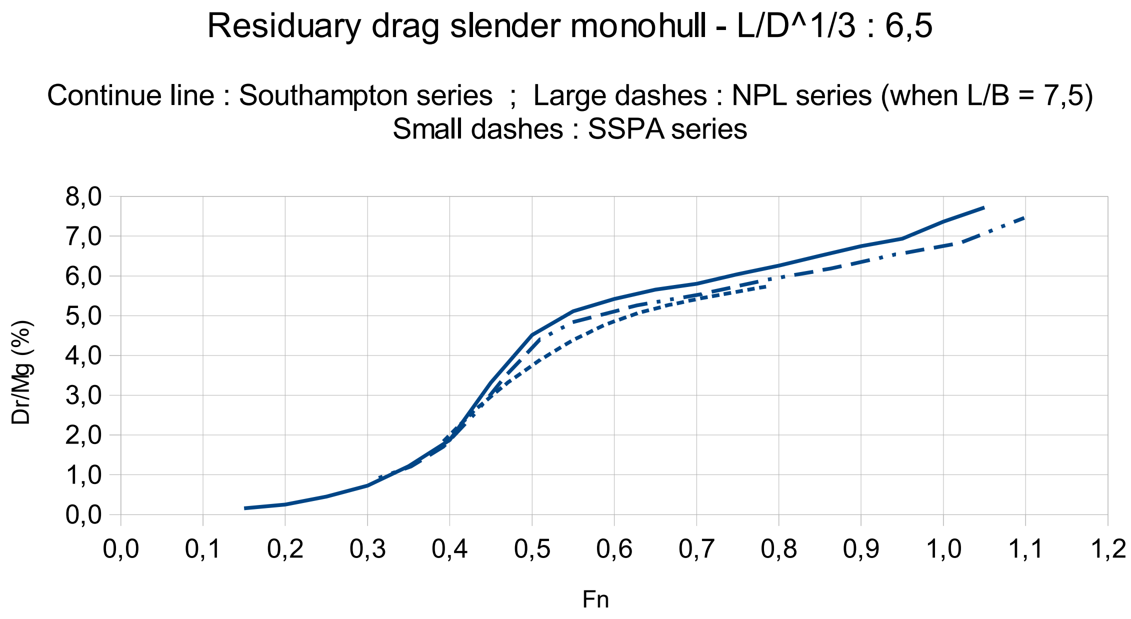
Comment : the figures show that the length displacement ratio Lw/D^1/3 , when constant, tends to uniformised the Dr/Mg curves, like erasing the influences of the 2 others ratios Lw/Bw and Bw/Tc (again, within hulls sharing the same Cb ~ 0,4). So it seems justify to average the curves sharing the same Lw/D^1/3 to lead to this synthesis :

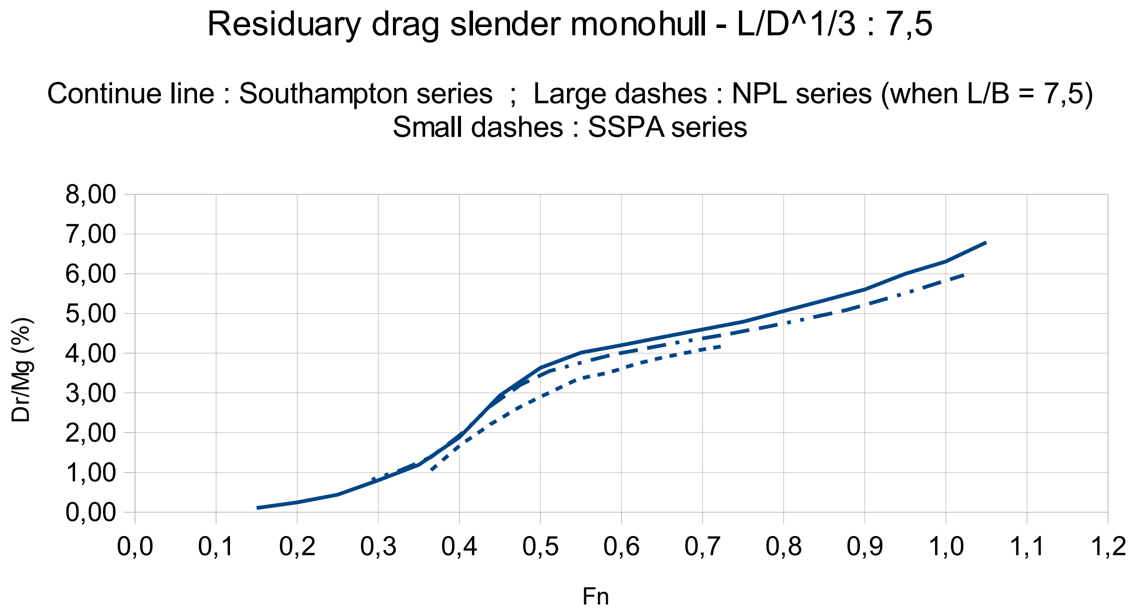


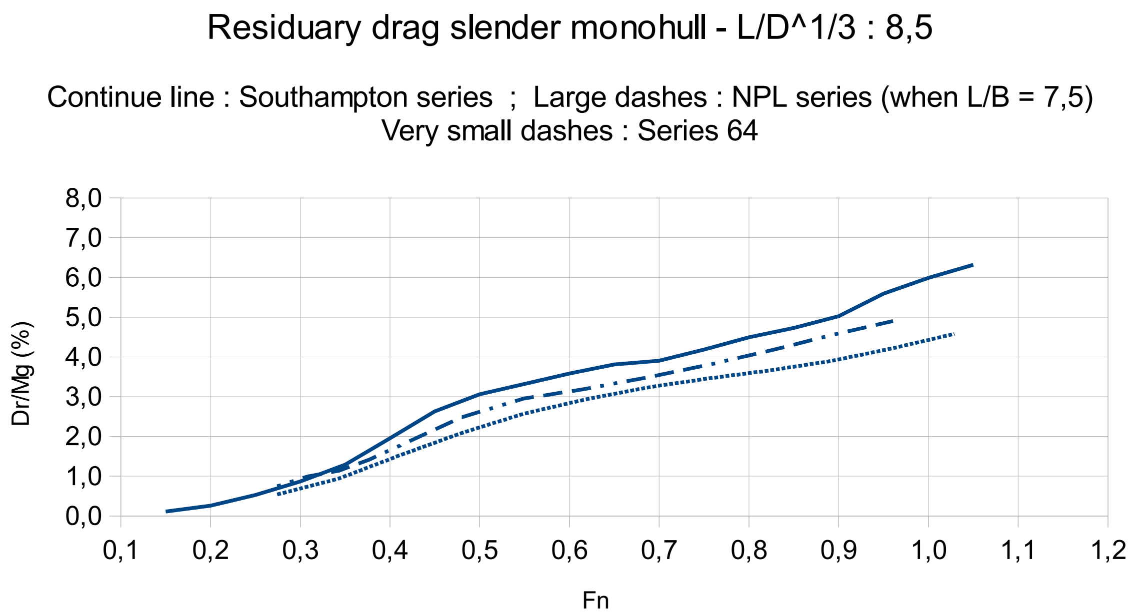
In a second step, we have compared these above results with the ones from previous model tests experiments, i.e. Series 64 (itself averaged by Oossanen), SSPA series, NPL series and put in the same formats >>>

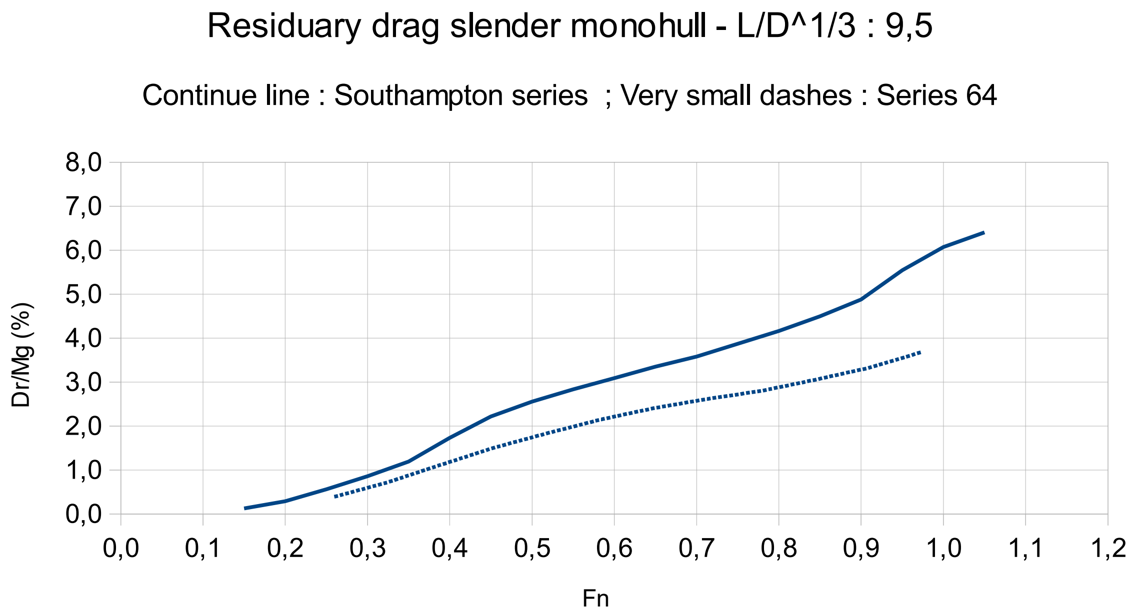
Series 64 (from Fig. 8, with Cb = 0,35 to 0,55 and L/B 8,5 to 18,3)
SSPA series (from Fig. 9, with Cb = 0,4 and L/B 4,6 to 8,2)
NPL series (from Fig. 14, with Cb 0,397 and L/B 7,5)

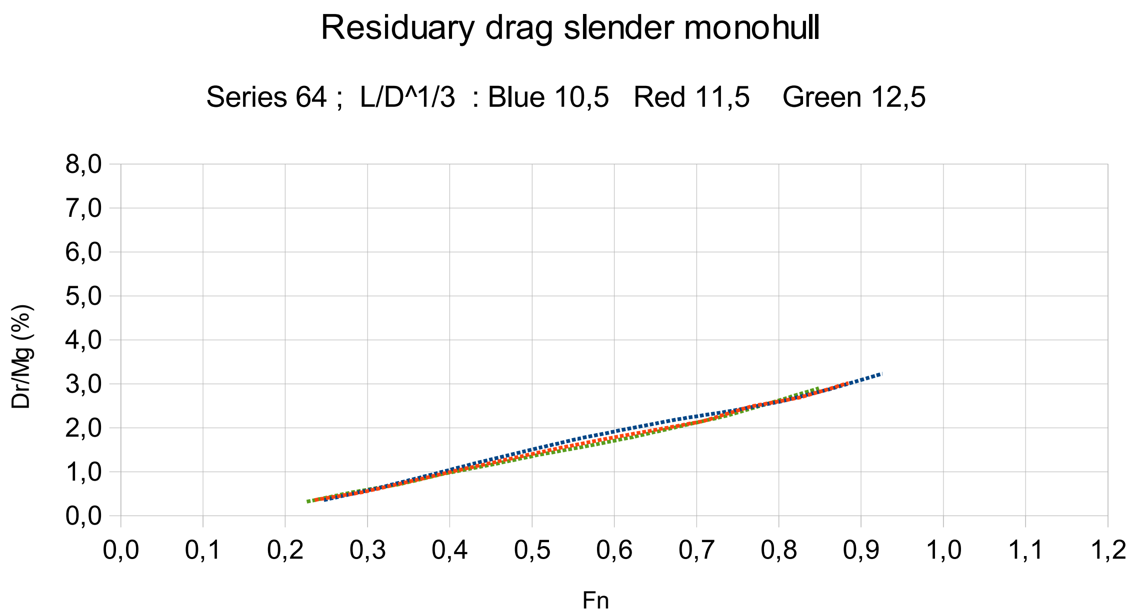
ref : https://www.oossanen.nl/beheer/wp-content/uploads/2013/02/petervanoossanen_-_resistance_prediction_of_small_high-speed_displacement_vessels.pdf






Residuary drag slender monohull - L/D^1/3 : 8,5
Continue line : Southampton series ; Large dashes : NPL series (when L/B = 7,5)
Very small dashes : Series 64
Dr/Mg (%)
8,0
7,0
6,0
5,0
4,0
3,0
2,0
1,0
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1,1
1,2
Fn


Residuary drag slender monohull - L/D^1/3 : 9,5
Continue line : Southampton series ; Very small dashes : Series 64
Dr/Mg (%)
8,0
7,0
6,0
5,0
4,0
3,0
2,0
1,0
0,0
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1,1
1,2
Fn



>>> one can note that for L/D^1/3 = 10,5 the hump becomes imperceptible (at Froude ~ 0,6), and finally is not visible for L/D^1/3 = 11,5 and 12,5, leading to a straight line.

2.4 Proposed formulations and figures to estimate the Residuary drag

From the previous analysis, two approaches can be proposed :

A : with using Lw/Bw + correction for Bw/Tc

B : with using Lw/D^1/3

Approach A : with using Lw/Bw + correction for Bw/Tc

Dr/Mg (%) = Function (Fn, Lwl/Bwl, when Bwl/Tc = 2) * Correction (when Bwl/Tc ≠ 2)

with : Dr : residuary drag ; Mg : weight of the monohull ; Fn : Froude number (based on Lwl)

Lwl : length waterline ; Bwl : beam waterline ; Tc : hull draft

Figure 1A. Function (when Bwl/Tc =2) :

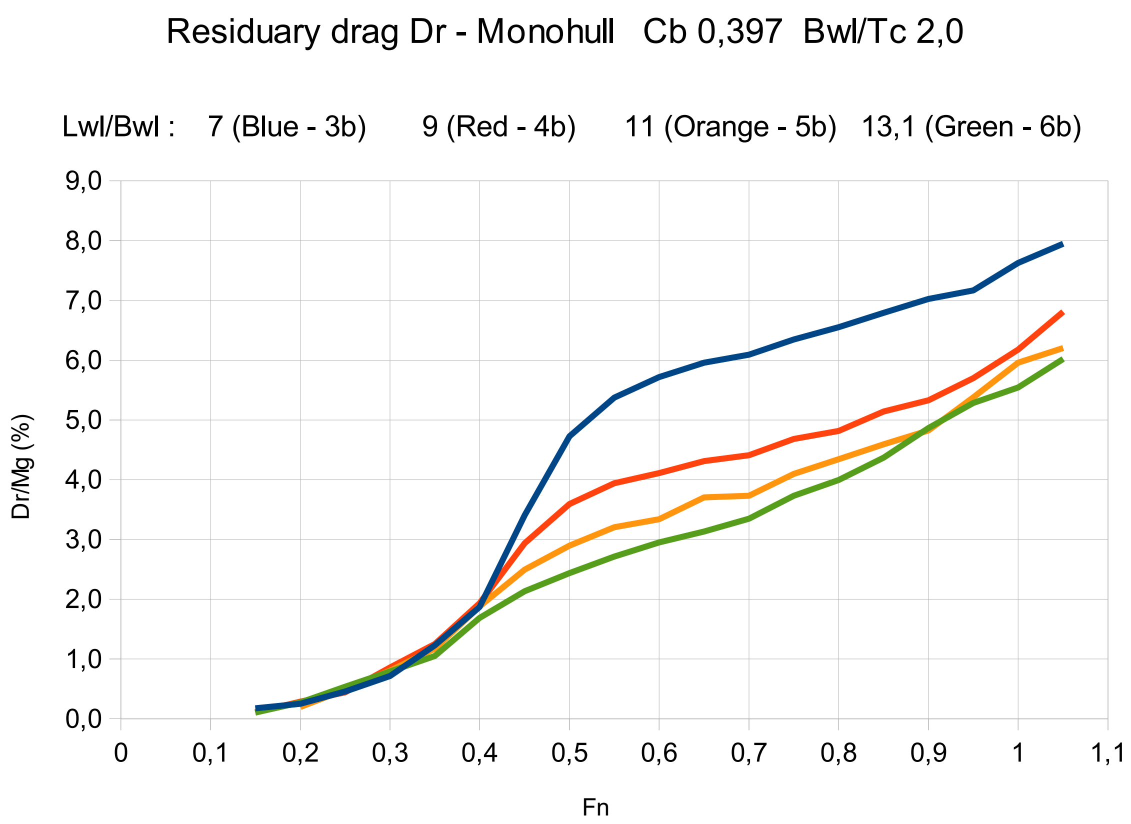
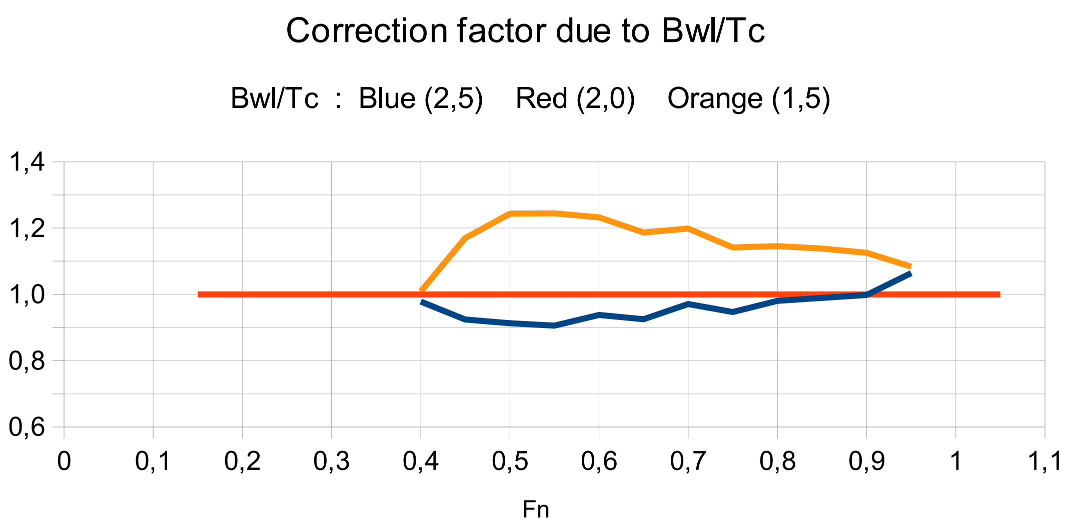


Figure 2A. Correction factor (when Bwl/Tc ≠ 2)



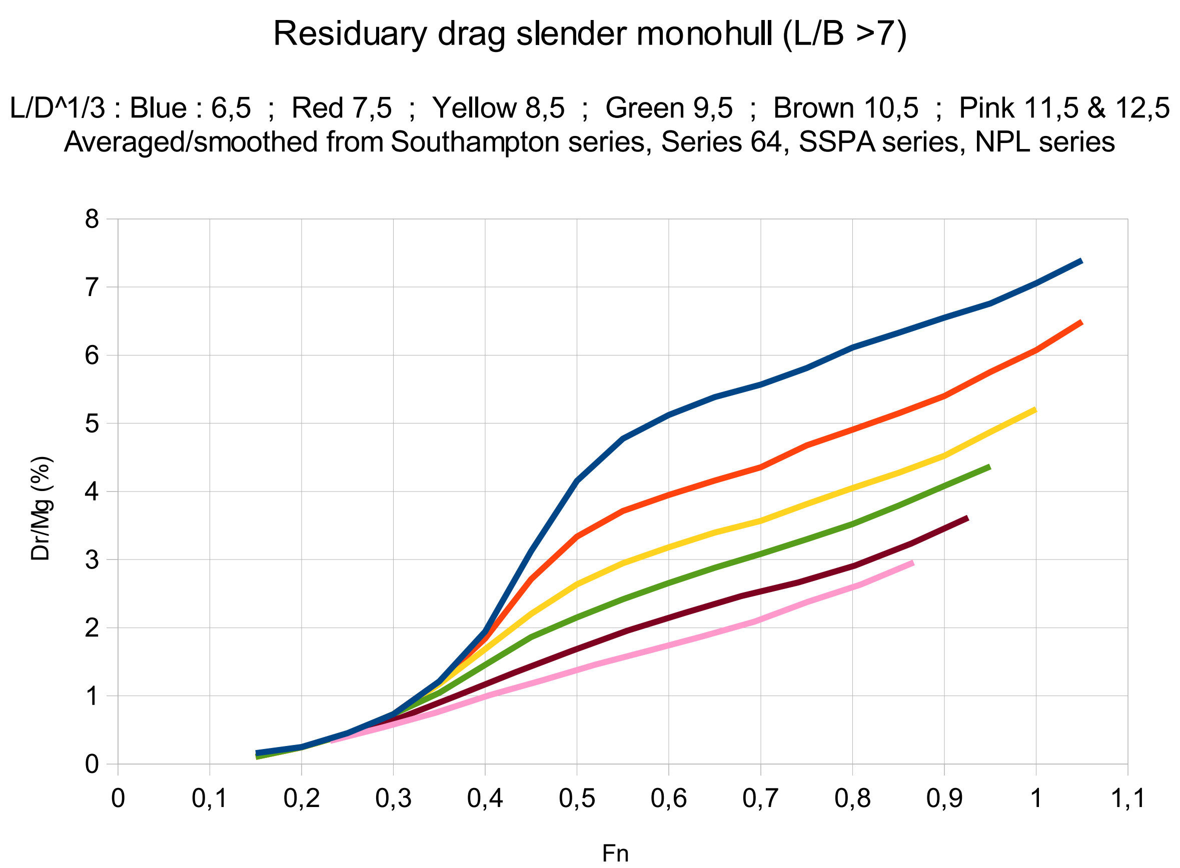
Approach B : with using Lw/D^1/3

This approach is in tune with this comment of Oonnasen in his paper : « …. Up to Fn value of 0,9, the result for the 3 B/T values are almost identical, leading to the observation that in the speed range between 0,4 to 0,9, the length displacement ratio is the only significant parameter »

Dr/Mg (%) = Function (Fn, Lwl/D^1/3)

with : Dr : residuary drag ; Mg : weight of the monohull ; Fn : Froude number (based on Lwl)
Lwl : length waterline ; D : Displacement

Figure 1B. Averaged/smoothed from the above analysis



3. The residuary drag estimation for an upright catamaran

The approach is simple : it is to add an amplification factor to the monohull residuary drag to take into account the interference between the two hulls, such as (still in adimensional) :

Dr/Mg (%) Catamaran = (1+K) * Dr/Mg (%) Monohull

, where K is function of S/Lwl , Lwl/Bwl, Bwl/Tc

K values are given in the following figures directly derived from the tests resuls (from Fig. 33 to 46d of the paper), covering S/Lwl = 0,3, 0,4 and 0,5 ; Lwl/Bwl = 7 to 15 ; Bwl/Tc = 1,5 to 2,5

Figure 3 :

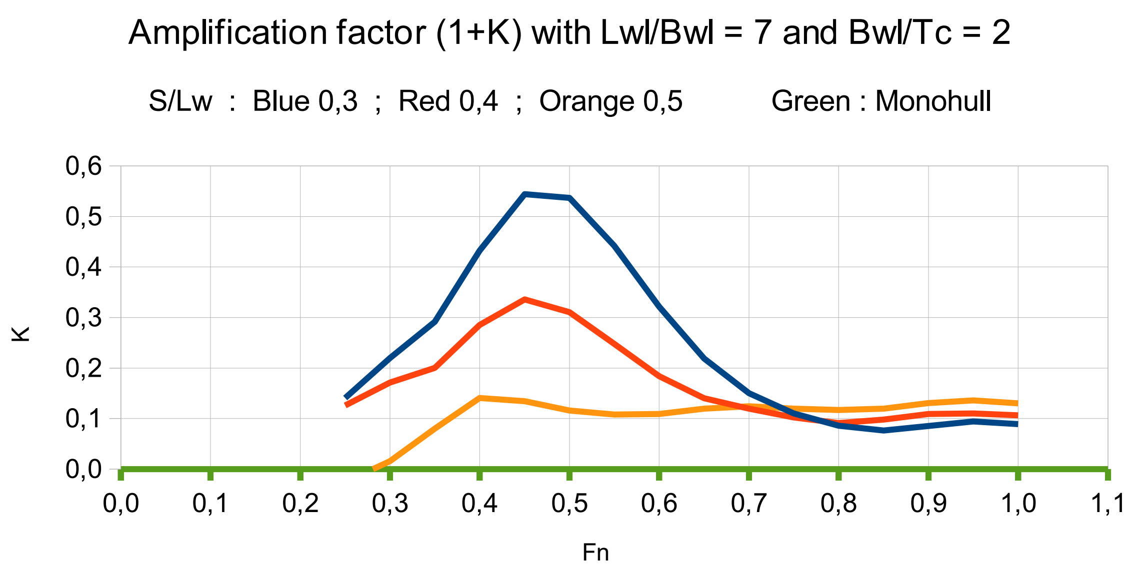


Figure 4 :

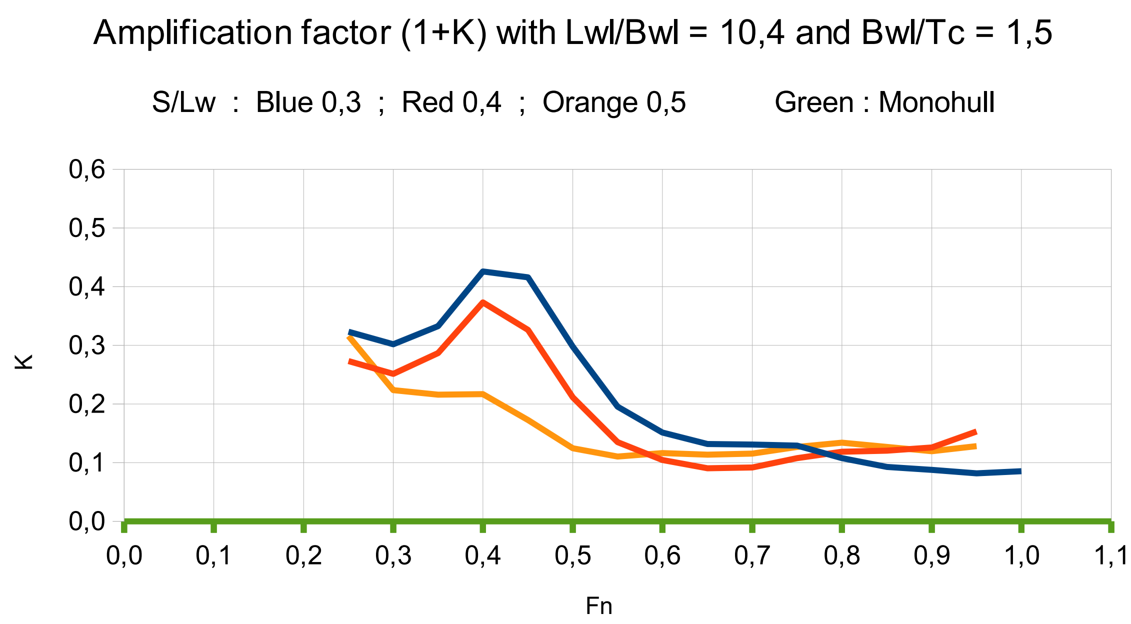


Figure 5 :

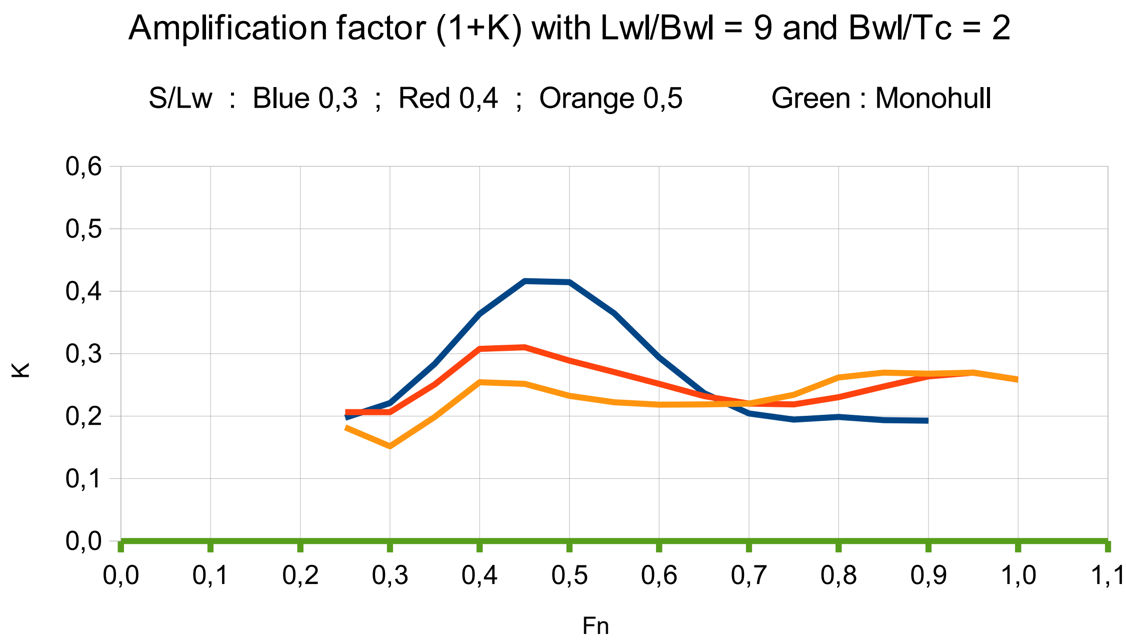


Figure 6 :

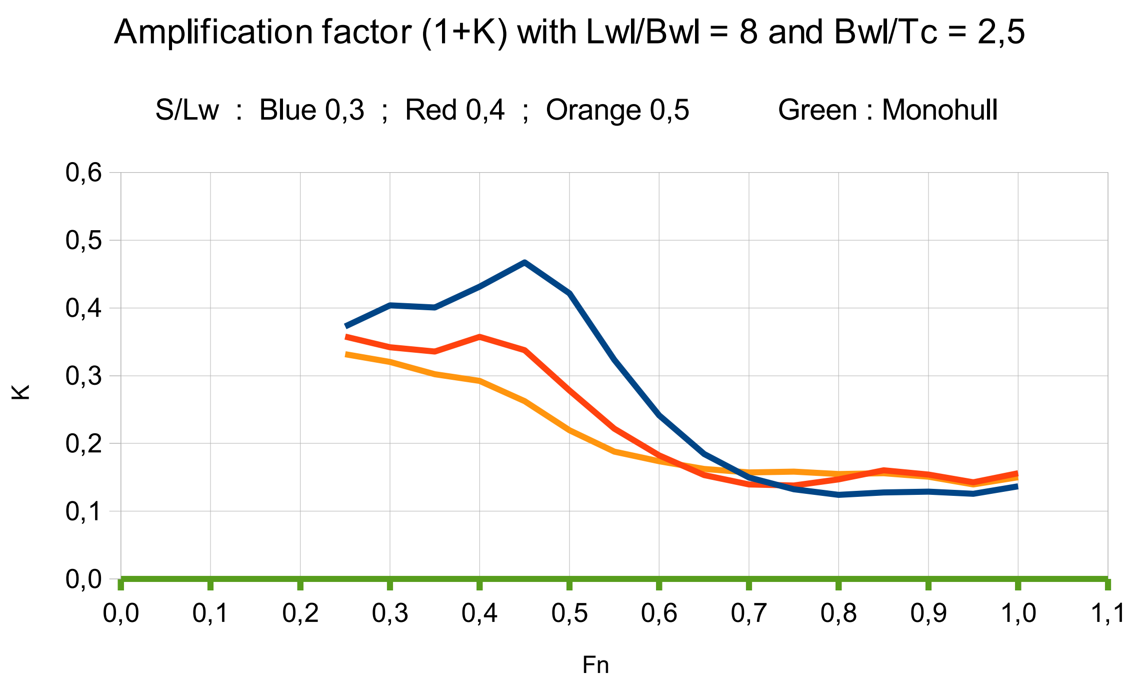


Figure 7 :

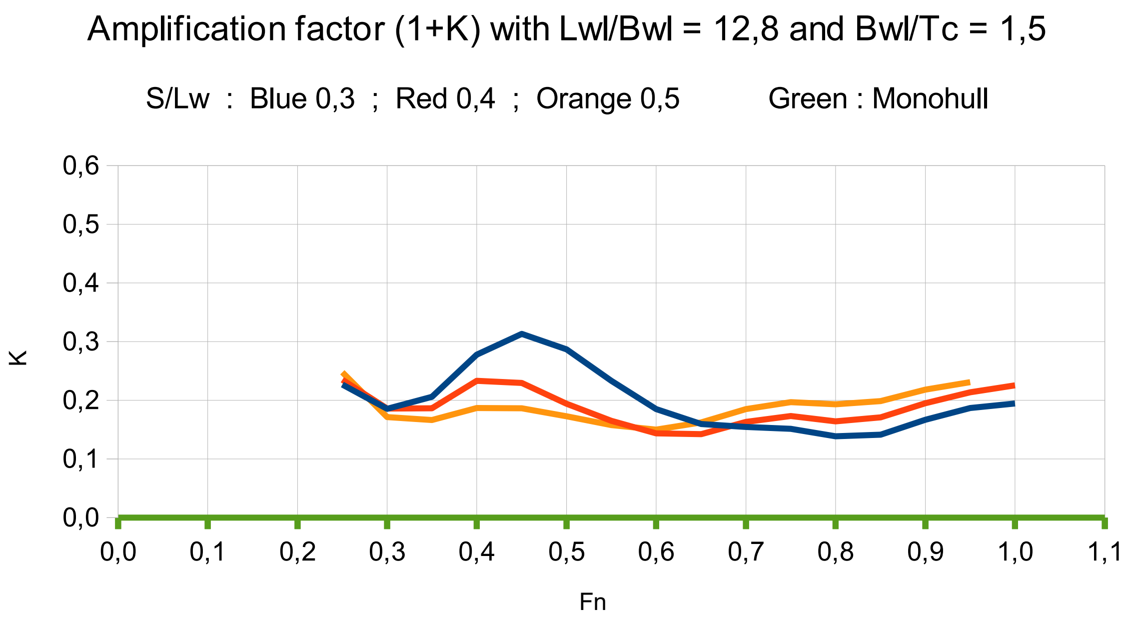


Figure 8 :

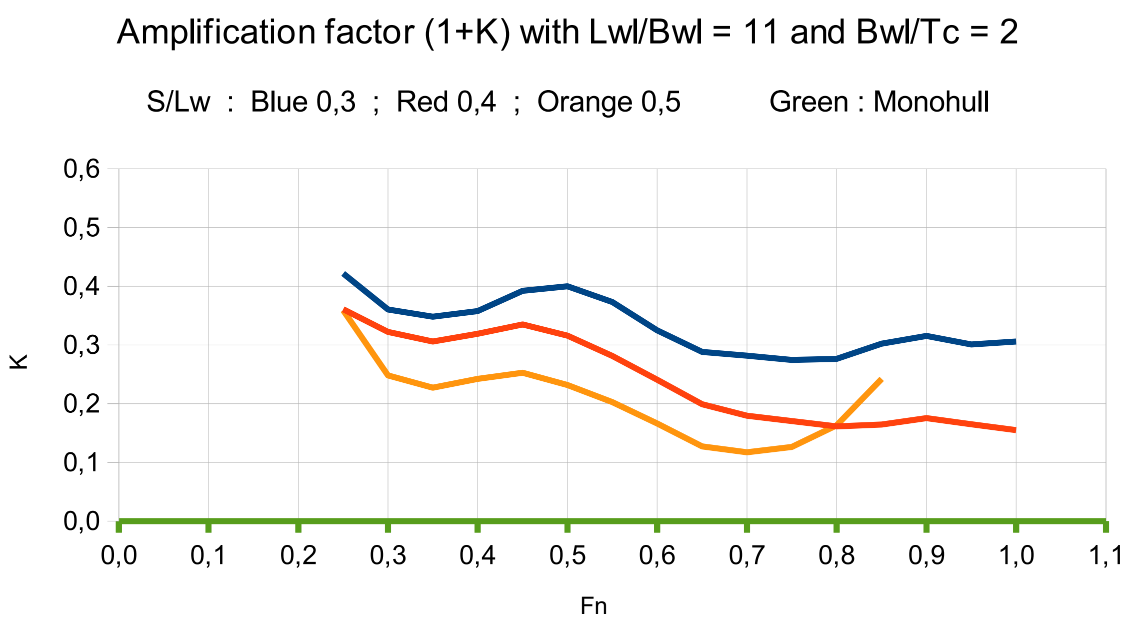


Figure 9 :

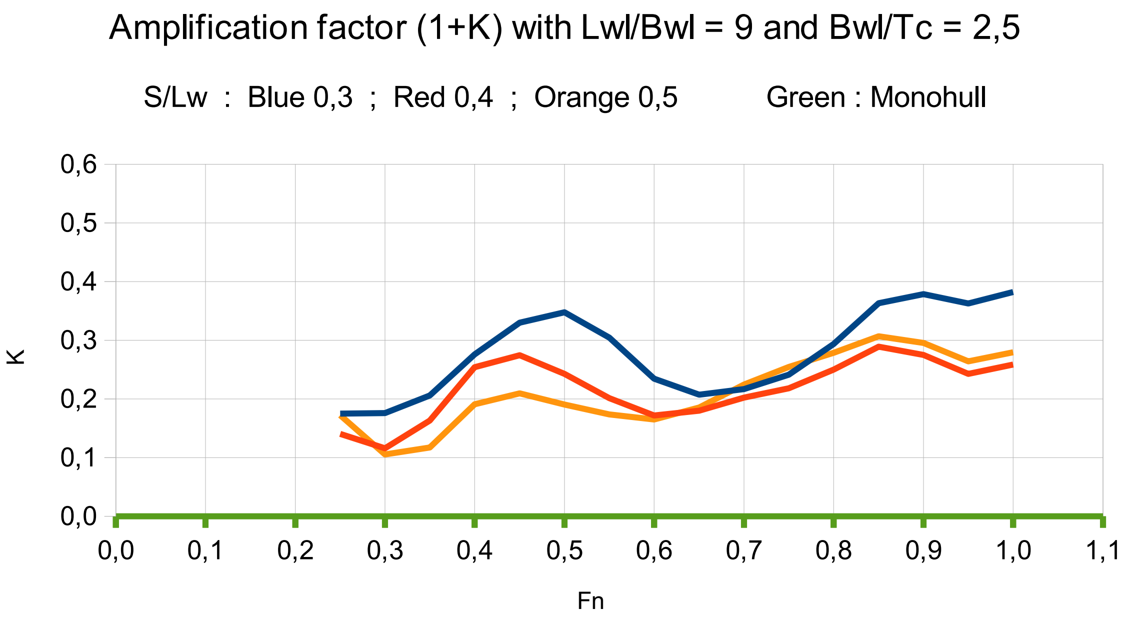


Figure 10 :

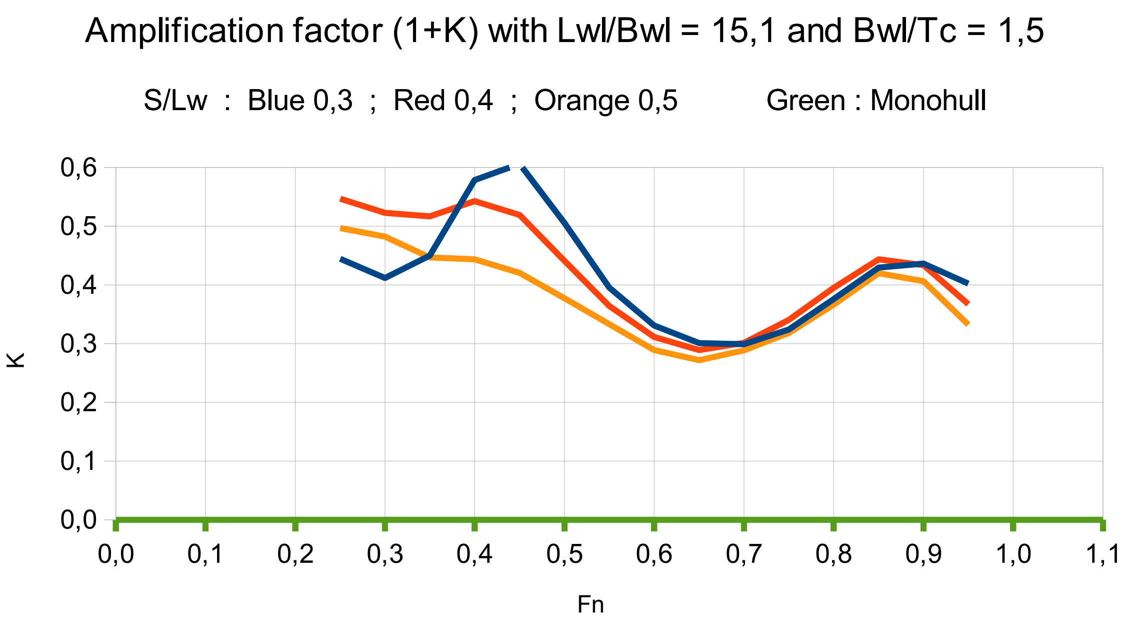


Figure 11 :

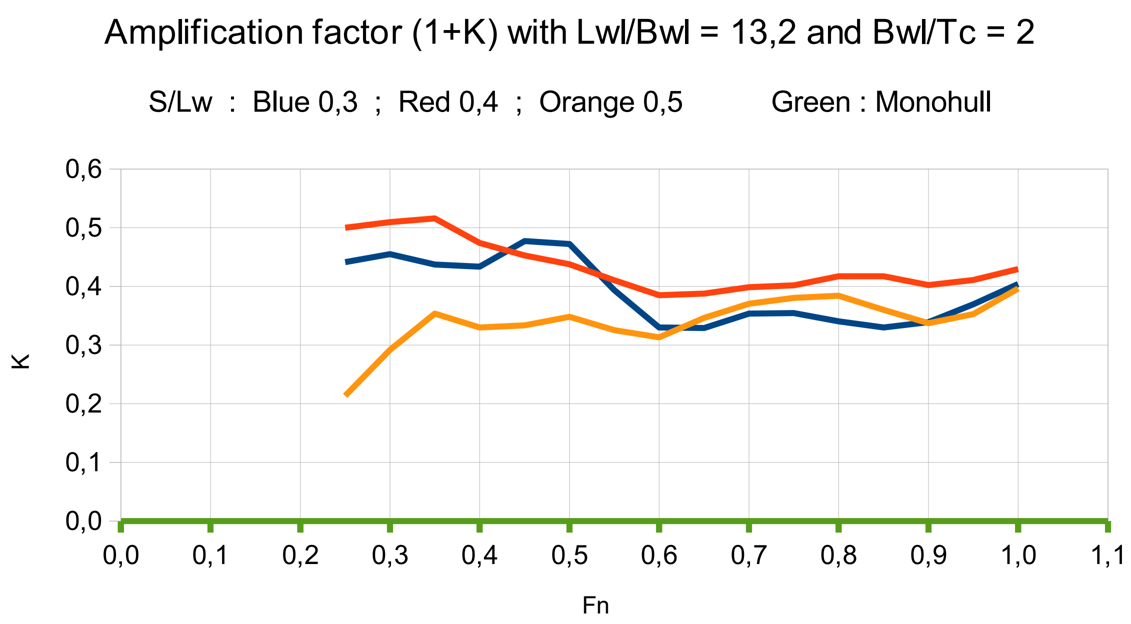
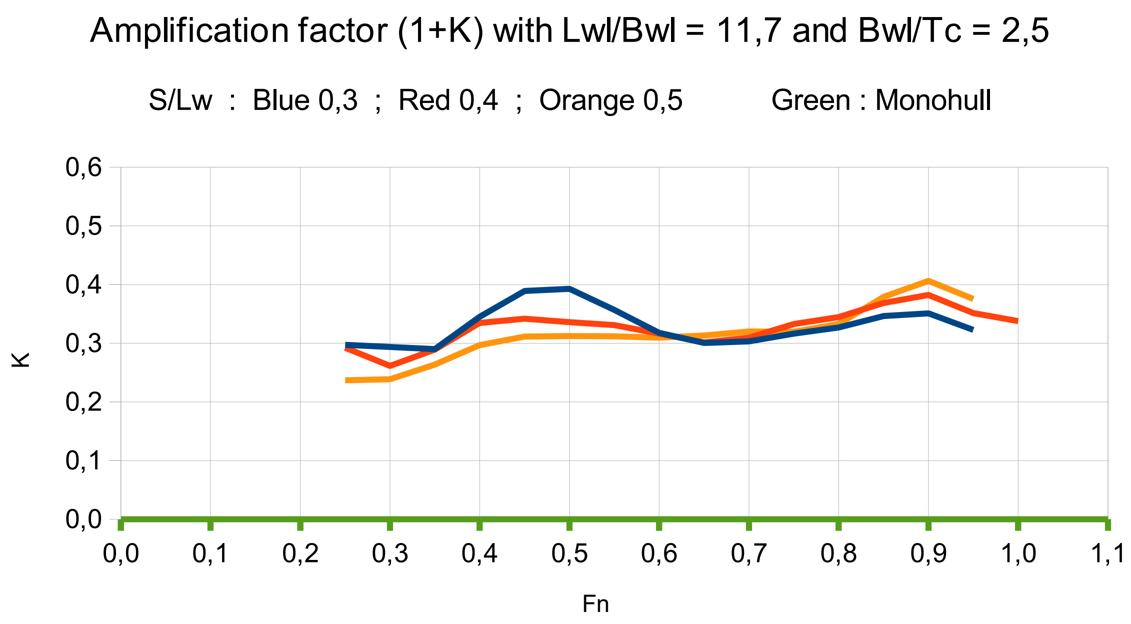


Figure 12 :



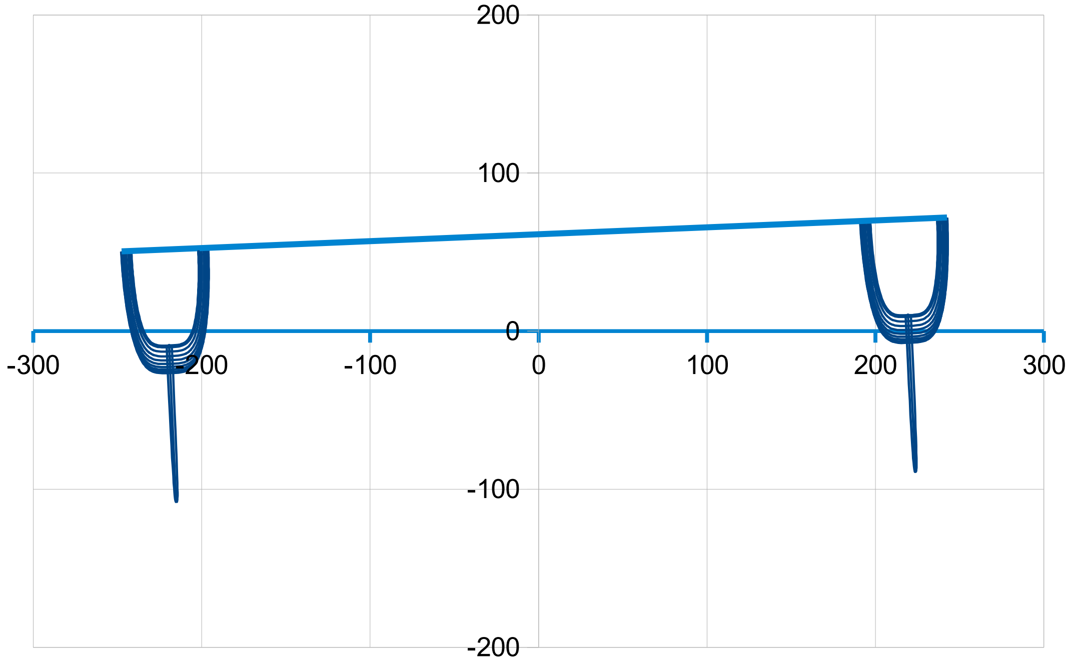
From these Figures 3 to 12 above, some comments :

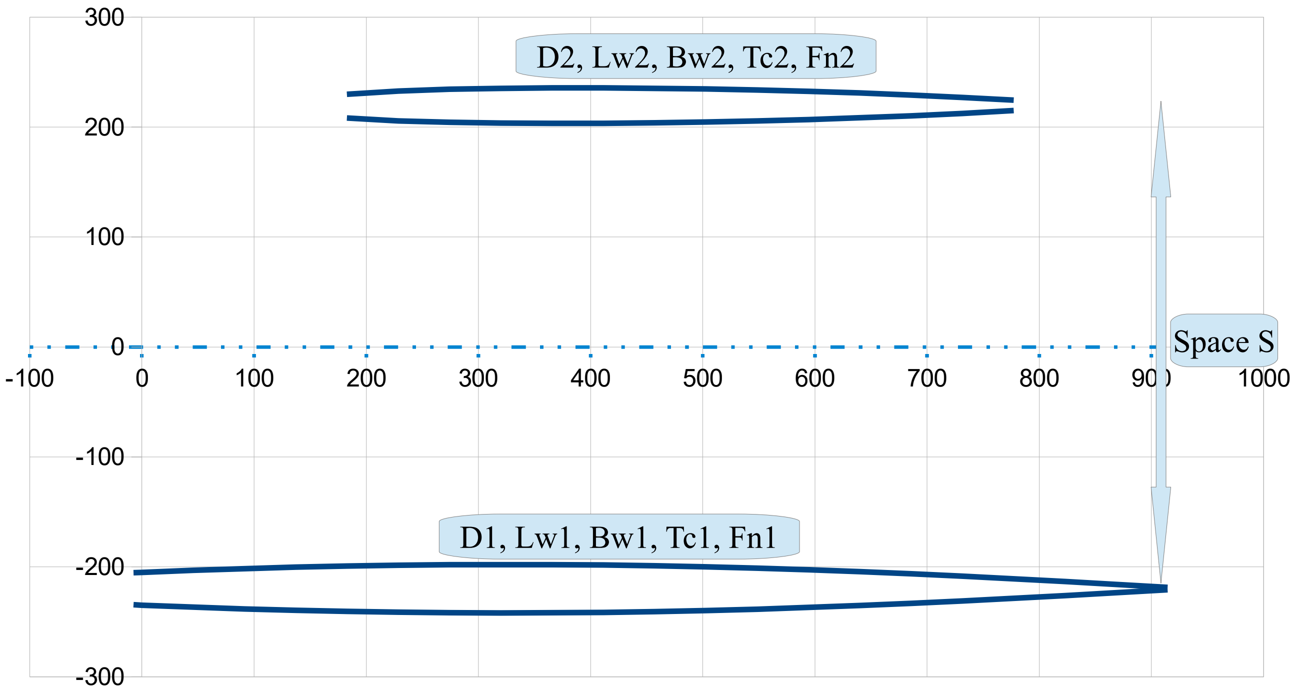
- of course, one can see that the amplification factor K is usually higher for smaller S/Lw, but one can note also some reverse trends at higher Froude > 0,7
- idem concerning Lwl/Bwl or Bwl/Tc : there is no uniform influence easy to capture within a simple law..

It is not evident to draw an interpolation formulation from these 10 figures, able to take account consistently of S/Lw, Lwl/Bwl and Bwl/Tc. So presently, the best solution for the user is to do himself the interpolation process with using the closest Figures corresponding to his set of input data.

4. The residuary drag estimation for the heeled catamaran

A heeled catamaran has two hulls with for each different Displacement D, Lwl, Bwl, Tc, Froude Fn :





Let's subsript 1 for the leeward hull and 2 for the windward one, the residuary drag is :

Dr = (1+K1) * Dr/Mg (Fn1, Lw1/Bw1, Bw1/Tc1) * D1
+ (1+K2) * Dr/Mg (Fn2, Lw2/Bw2, Bw2/Tc2) * D2

Amplification factor | Monohull residuary drag coefficient | Displacement

The issue is to empirically estimate K1 and K2, in absence of ad hoc test results :

Let's consider K1 or K2 the amplification factor corresponding to an upright catamaran with respectively two leeward hulls or two windward hulls spaced with S.

It is somewhat evident that the influence of Hull 2 winward on Hull 1 leeward residuary drag is less than when applying K1 **>>> proposition :**

- let's consider an influence proportional to the Displacement ratio :
  K1cor = K1 * (D2/D1)
  If D2 = D1 , the upright configuration, we recover K1
  If D2 = 0 , when the windward hull is flying over the water, we recover 1, i.e. the leeward hull is a monohull

Reversely, how about the influence of hull 1 on the residuary drag of hull 2 ?
It seems logical that the influence is higher than when considering 2 hull2. On the other hand, that cannot be proportional with D1/D2 because when D2 tends to zero (Hull 2 flying mode), the residuary drag would tend to a fix value instead of zero, which is impossible. **>>> proposition :**

- let's consider an influence proportional to the sqare root of the displacement ration :
  K2cor = K2 * (D1/D2)^0,5

Then the complete formulation becomes :
Dr = (1+K1*(D2/D1)) * Dr/Mg (Fn1, Lw1/Bw1, Bw1/Tc1) * D1 + (1+K2*(D1/D2)^0,5) * Dr/Mg (Fn2, Lw2/Bw2, Bw2/Tc2) * D2

, with K = function of (S/Lw, Lw/Bw, Bw/Tc) for each hull considered separately in an upright cata configuration

, and to check that :

- when D2 = D1 :
  >>> 1+K1 = 1+K2 = 1+K the amplification factor of the upright catamaran
- when D2 = 0 , i.e. the windward hull above the water :
  >>> 1+K1*(D2/D1) = 1 , i.e. leeward hull = sleder monohull
  >>> (1 + K2 *(D1/D2)^0,5) * Dr/Mg * D2 = 0 , no drag for the windward hull

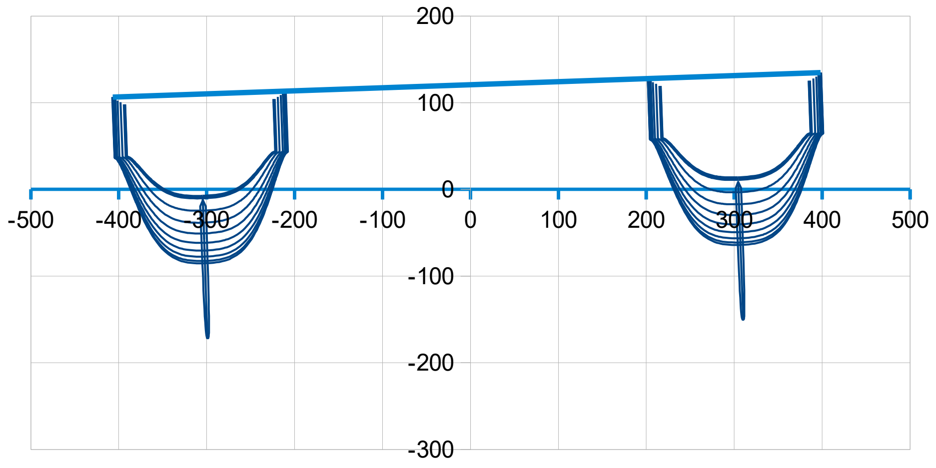
5. Numerical examples

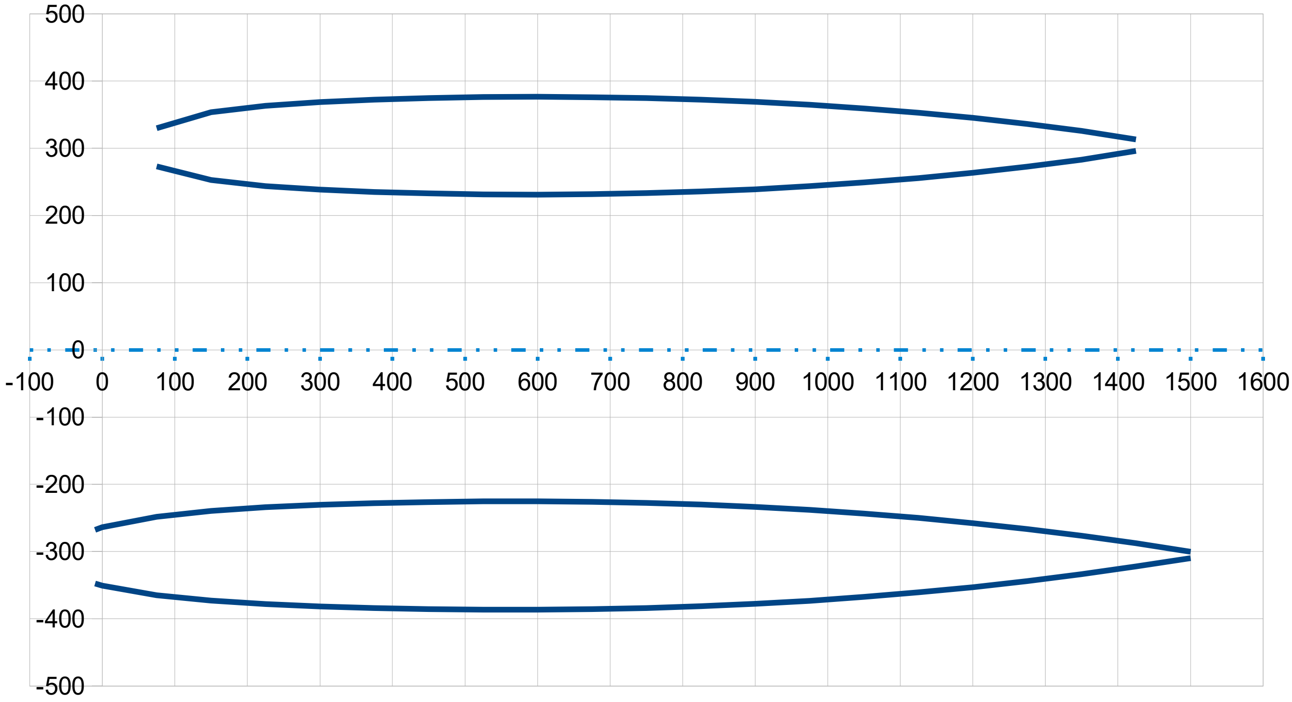
For a 16m cruising catamaran (L/B ~ 9,7 when upright) and 3 speed/heel cases, and for a 9m racing catamaran (L/B ~ 22,7, when upright) and 1 speed/heel case. Computations are done with the 2 approaches A and B for the Monohull Dr/Mg estimation, and the approach B value is kept for the final computations in sailing catamaran mode :

- Case 1 : 16m cruising cata, speed 7 Knots (Froude ~ 0,30) with an heel angle of 2°
  >>> Residuary drag / Friction drag proportion is 61% / 39%
- Case 2 : 16m cruising cata, speed 12 knots (Froude ~ 0,50) with an heel angle of 4°
  >>> Residuary drag / Friction drag proportion is 69% / 31%
- Case 3 : speed 18 knots (Froude ~ 0,75) with an heel angle of 7°
  >>> Residuary drag / Friction drag proportion is 63% / 37%
- Case 4 : 9m racing cata, speed 12 knots (Froude ~ 0,64) with an heel angle of 4,5° (windward hull full flying)
  >>> Residuary drag / Friction drag proportion is 28% / 72%

Step by step computations are given here below :

Case 1 : 16m Cata assumed at speed of 7 knots with an heel angle of 2° - Input data		
S (Space between hull axis, m)	6,1	
	leeward hull 1	**windward hull 2**
Lw (m)	16,00	14,29
Bw (m)	1,61	1,46
Tc (m)	0,86	0,65
Displacement D (N)	94060 (62%)	57507 (38%)
Cb	0,421	0,424
Cp	0,572	0,572
Hull wetted surface (m2)	29,02	21,55
Aft transom height (cm) (negative = immersion)	-5,4	15,9
>> Lw/Bw	9,93	9,82
>> Bw/Tc	1,87	2,24
For approach B >> Lw/D1/3	7,59	7,99
>> S/Lw	0,38	0,43
>> Fn	0,29	0,30





<u>The leeward hull :</u>

Residuary drag of the leeward hull as a monohull :

> **Approach A :**
> From Fig. 1A with Lw/Bw = 9,93 and Fn = 0,29 >>> Dr/Mg (%) ~ 0,85
> From Fig.2A with Bw/Tc = 1,87 and Fn = 0,29 >>> Correction factor ~ 1,0
> **A >>> Dr/Mg (%, Monohull)** ~ 0,8 * 1,0 **~ 0,85**
>
> **Approach B :**
> From Fig. 1B with Lw/D^1/3 = 7,59 and Fn = 0,29 >>> Dr/Mg (%) ~ 0,85
> **B >>> Dr/Mg (%, Monohull) ~ 0,85**

Residuary drag of the leeward hull as part of the catamaran, with S/Lw = 0,38 :

From Fig. 4 with Lw/Bw = 10,4 and Bw/Tc = 1,5 :

S/Lw = 0,38 and Fn = 0,29 >>> K ~ 0,27

From Fig. 7 with Lw/Bw = 12,8 and Bw/Tc = 1,5 :

S/Lw = 0,38 and Fn = 0,29 >>> K ~ 0,20

>>> So for Lw/Bw = 9,93 , by linear interpolation >>> K ~ 0,272

From Fig. 5 with Lw/Bw = 9 and Bw/Tc = 2,0 :

S/Lw = 0,38 and Fn = 0,29 >>> K ~ 0,21

From Fig. 8 with Lw/Bw = 11 and Bw/Tc = 2,0 :

S/Lw = 0,38 and Fn = 0,29 >>> K ~ 0,35

>>> So for Lw/Bw = 9,93 , by linear interpolation >>> K ~ 0,275

So finally for Bw/Tc = 1,87 >>> **K1** ~ 0,272 + (0,275-0,272)/(2,0-1,5)(1,87-1,5) **~ 0,274**

>>> Amplification factor = 1 + K1 (D2/D1) = 1 + 0,274 * (57507/94060) = **1,17**

>>> Residuary drag of the leeward hull : 1,17 * (0,85/100) * 94060 **~ 935 N**

<u>The windward hull :</u>

Residuary drag of the windward hull as a monohull :

Approach A :

From Fig. 1A with Lw/Bw = 9,82 and Fn = 0,30 >>> Dr/Mg (%) ~ 0,9

From Fig.2A with Bw/Tc = 2,24 and Fn = 0,3 >>> Correction factor ~ 1,0

A >>> Dr/Mg (%, Monohull) ~ 0,9 * 1,0 **~ 0,9**

Approach B :

From Fig. 1B with Lw/D^1/3 = 7,99 and Fn = 0,30 >>> Dr/Mg (%) ~ 0,9

B >>> Dr/Mg (%, Monohull) ~ 0,9

Residuary drag of the leeward hull as part of the catamaran, with S/Lw = 0,43 :

From Fig. 5 with Lw/Bw = 9 and Bw/Tc = 2,0 :

S/Lw = 0,43 and Fn = 0,3 >>> K ~ 0,18

From Fig. 8 with Lw/Bw = 11 and Bw/Tc = 2,0 :

S/Lw = 0,43 and Fn = 0,3 >>> K ~ 0,3

>>> So for Lw/Bw = 9,82 , by linear interpolation >>> K ~ 0,229

From Fig. 9 with Lw/Bw = 9 and Bw/Tc = 2,5 :

S/Lw = 0,43 and Fn = 0,3 >>> K ~ 0,11

From Fig. 12 with Lw/Bw = 11,7 and Bw/Tc = 2,5 :

S/Lw = 0,43 and Fn = 0,3 >>> K ~ 0,26

>>> So for Lw/Bw = 9,82 , by linear interpolation >>> K ~ 0,156

So finally for Bw/Tc = 2,24 >>> **K2** ~ 0,229 + (0,156-0,229)/(2,5-2,0)(2,5-2,24) **~ 0,191**

>>> amplification factor = 1 + K2 (D1/D2)^0,5 = 1 + 0,191 * (94060/57507)^0,5 ~ **1,24**
>>> Residuary drag of the leeward hull : 1,24 * (0,9/100) * 57507 **~ 642 N**

>>> Total Residuary drag = 935 (leeward) + 642 (windward) = 1577 N

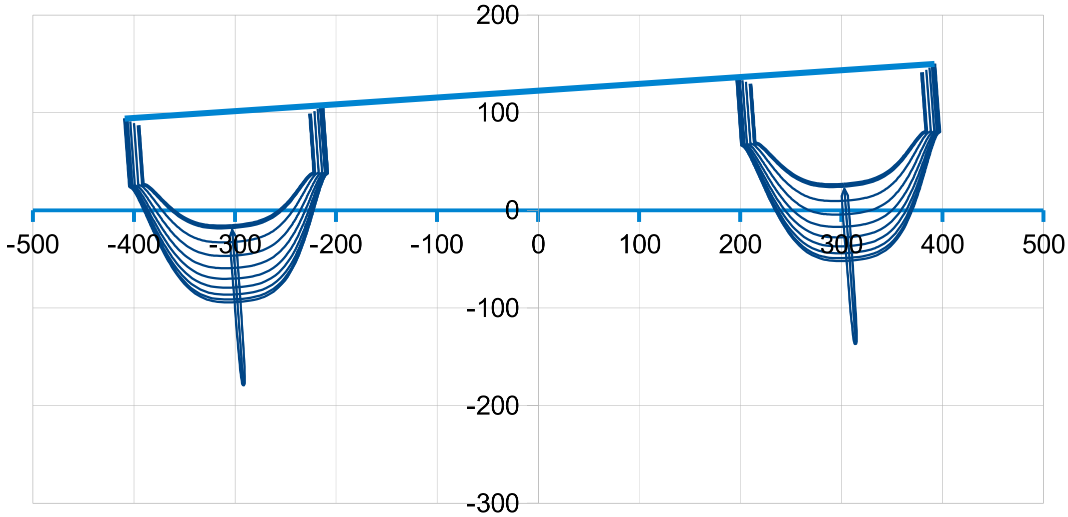
Comparison with the friction drag of the hulls at 7 knots :

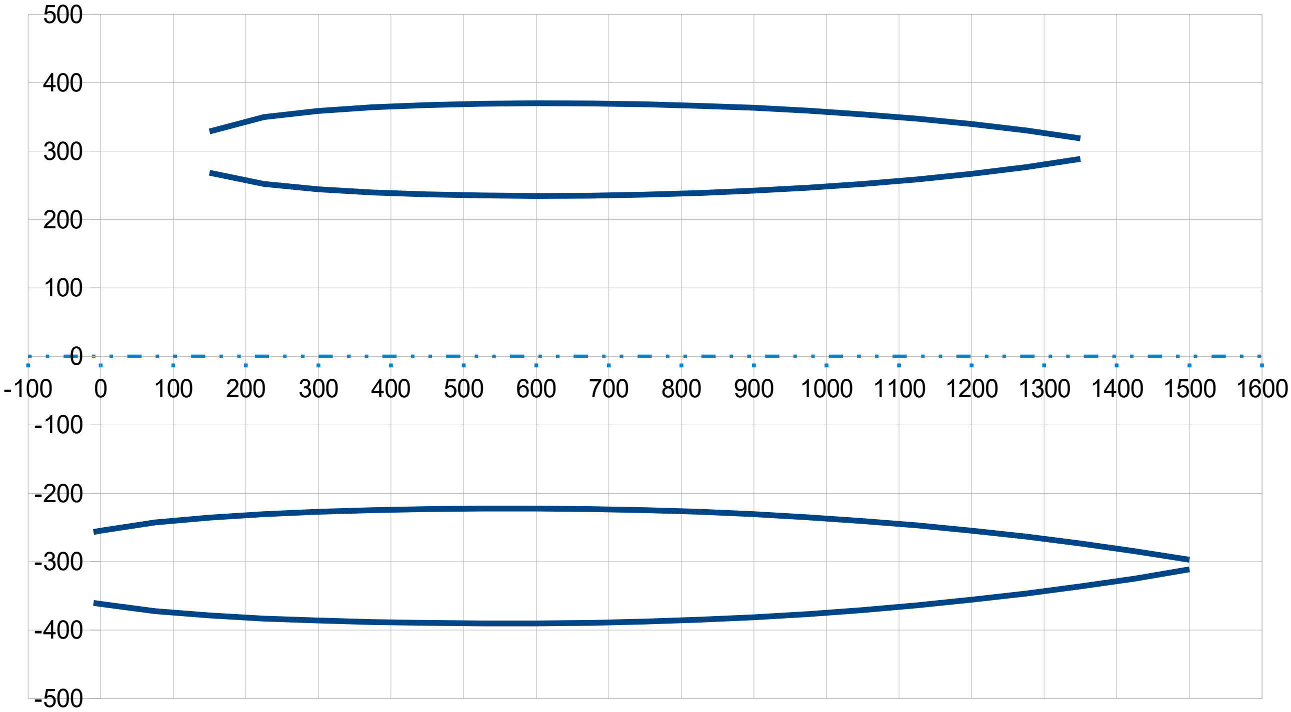
Leeward hull	**Windward hull**
Sw hull = 29,02 m2	Sw = 21,55 m2
Lw = 16 m	Lw = 14,29 m
Re (with using 0,7 Lw) = 4,03 E07	Re (with using 0,7 Lw) = 3,60 E07
Cf (ITTC 57) = 0,00239	Cf (ITTC 57) = 0,00243
>>> Df Hull = 460 N	**>>> Df Hull= 348 N**
Sw daggerboard = 2,39 m2	Sw daggerboard = 2,39 m2
Root chord = 0,7 m	Root chord = 0,7 m
Re (with using the root chord) = 2,52 E06	Re (with using the root chord) = 2,52 E06
Cf (ITTC 57) = 0,00387	Cf (ITTC 57) = 0,00387
>>> Df daggerboard = 61 N	**>>> Df daggerboard = 61 N**
Sw rudder = 1,15 m2	Sw rudder = 1,15 m2
Root chord = 0,4 m	Root chord = 0,4 m
Re (with using the root chord) = 1,44 E06	Re (with using the root chord) = 1,44 E06
Cf (ITTC 57) = 0,00434	Cf (ITTC 57) = 0,00434
>>> Df rudder = 33 N	**>>> Df rudder = 33 N**
>>> Df total leeward = 554 N	>>> Df total windward = 442 N

>>> Total Friction drag for the 2 hulls (+ daggerboard and rudder) : 996 N

Comment : *at 7 knots for this 16 m catamaran with a moderate L/B (~ 9,7 when upright), we are at about Froude 0,3 for the 2 hulls, the total wave drag is 1577 N to compare to 996 N for the friction component, so a 61% / 39% proportion.*

Case 2 : 16m Cata assumed at speed of 12 knots with an heel angle of 4° - Input data		
S (Space between hull axis, m)	6,1	
	leeward hull 1	**windward hull 2**
Lw (m)	16,00	12,67
Bw (m)	1,68	1,36
Tc (m)	0,95	0,53
Displacement D (N)	111447 (73,5%)	40120 (26,5%)
Cb	0,434	0,440
Cp	0,592	0,594
Hull wetted surface (m2)	32,04	17,50
Aft transom height (cm) (negative = immersion)	-13,5	28,8
>> Lw/Bw	9,54	9,35
>> Bw/Tc	1,76	2,57
For approach B >> Lw/D1/3	7,18	7,99
>> S/Lw	0,38	0,48
>> Fn	0,49	0,55





The leeward hull :

Residuary drag of the leeward hull as a monohull :

Approach A :
From Fig. 1A with Lw/Bw = 9,54 and Fn = 0,49 >>> Dr/Mg (%) ~ 3,3
From Fig. 2A with Bw/Tc = 1,76 and Fn = 0,49 >>> Correction factor ~ 1,12
A >>> Dr/Mg (Monohull) ~ 3,3 * 1,12 ~ **3,7**

Approach B :
From Fig. 1B with Lw/D^1/3 = 7,18 and Fn = 0,49 >>> Dr/Mg (%) ~ 3,49
B >>> Dr/Mg (%, Monohull) ~ 3,49

Residuary drag of the leeward hull as part of the catamaran, with S/Lw = 0,38 :

From Fig. 4 with Lw/Bw = 10,4 and Bw/Tc = 1,5 :
S/Lw = 0,38 and Fn = 0,49 >>> K ~ 0,25
From Fig. 7 with Lw/Bw = 12,8 and Bw/Tc = 1,5 :
S/Lw = 0,38 and Fn = 0,49 >>> K ~ 0,23
>>> So for Lw/Bw = 9,54 , by linear interpolation >>> K ~ 0,257

From Fig. 5 with Lw/Bw = 9 and Bw/Tc = 2,0 :
S/Lw = 0,38 and Fn = 0,49 >>> K ~ 0,31
From Fig. 8 with Lw/Bw = 11 and Bw/Tc = 2,0 :
S/Lw = 0,38 and Fn = 0,49 >>> K ~ 0,33
>>> So for Lw/Bw = 9,54 , by linear interpolation >>> K ~ 0,315

So finally for Bw/Tc = 1,76 >>> **K1** ~ 0,257 + (0,315-0,257)/(2,0-1,5)(1,76-1,5) **~ 0,287**

>>> Amplification factor = 1 + K1 (D2/D1) = 1 + 0,287 * (40120/111447) = **1,10**

>>> Residuary drag of the leeward hull, with using 3,49 from the approach B :
1,10 * (3,49/100) * 111447 **~ 4278 N**

<u>The windward hull :</u>

Residuary drag of the windward hull as a monohull :

Approach A :
From Fig. 1A with Lw/Bw = 9,35 and Fn = 0,55 >>> Dr/Mg (%) ~ 3,9
From Fig. 2A with Bw/Tc = 2,57 and Fn = 0,55 >>> Correction factor ~ 0,9
A >>> Dr/Mg (Monohull) ~ 3,9 * 0,9 ~ **3,51**

Approach B :
From Fig. 1B with Lw/D^1/3 = 7,99 and Fn = 0,55 >>> Dr/Mg (%) ~ 3,33
B >>> Dr/Mg (%, Monohull) ~ 3,33

Residuary drag of the leeward hull as part of the catamaran, with S/Lw = 0,48 :

From Fig. 9 with Lw/Bw = 9 and Bw/Tc = 2,5 :
S/Lw = 0,48 and Fn = 0,55 >>> K ~ 0,18
From Fig. 12 with Lw/Bw = 11,7 and Bw/Tc = 2,5 :
S/Lw = 0,48 and Fn = 0,55 >>> K ~ 0,32
>>> So for Lw/Bw = 9,35 , by linear interpolation >>> K ~ 0,185

Bw/Tc = 2,57 being close enough to 2,50, one can adopt **K2 ~ 0,185** without anymore complication

>>> amplification factor = 1 + K2 (D1/D2)^0,5 = 1 + 0,185 * (111447/40120)^0,5 ~ **1,31**

>>> Residuary drag of the leeward hull, with using 3,33 from the approach B :
1,31 * (3,33/100) * 40120 **~ 1750 N**

>>> Total Residuary drag = 4278 (leeward) + 1750 (windward) = 6028 N

Comparison with the friction drag of the hulls at 12 knots :

Leeward hull	**Windward hull**
Sw hull = 32,04 m2	Sw = 17,50 m2
Lw = 16 m	Lw = 12,67 m
Re (with using 0,7 Lw) = 6,91 E07	Re (with using 0,7 Lw) = 4,32 E06

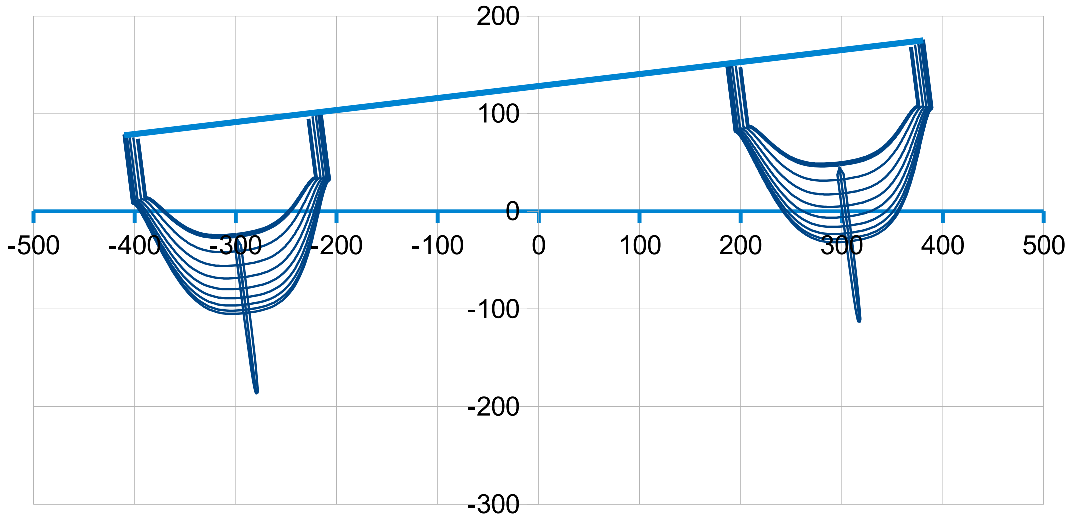
Cf (ITTC 57) = 0,00220	Cf (ITTC 57) = 0,00228
>>> Df Hull = 1376 N	**>>> Df Hull= 778 N**
Sw daggerboard = 2,39 m2	Sw daggerboard = 2,39 m2
Root chord = 0,7 m	Root chord = 0,7 m
Re (with using the root chord) = 4,32 E06	Re (with using the root chord) = 4,32 E06
Cf (ITTC 57) = 0,00349	Cf (ITTC 57) = 0,00349
>>> Df daggerboard = 163 N	**>>> Df daggerboard = 163 N**
Sw rudder = 1,15 m2	Sw rudder = 1,15 m2
Root chord = 0,4 m	Root chord = 0,4 m
Re (with using the root chord) = 2,47 E06	Re (with using the root chord) = 2,47 E06
Cf (ITTC 57) = 0,00389	Cf (ITTC 57) = 0,00389
>>> Df rudder = 87 N	**>>> Df rudder = 87 N**
>>> Df leeward = 1626 N	>>> Df windward = 1028 N

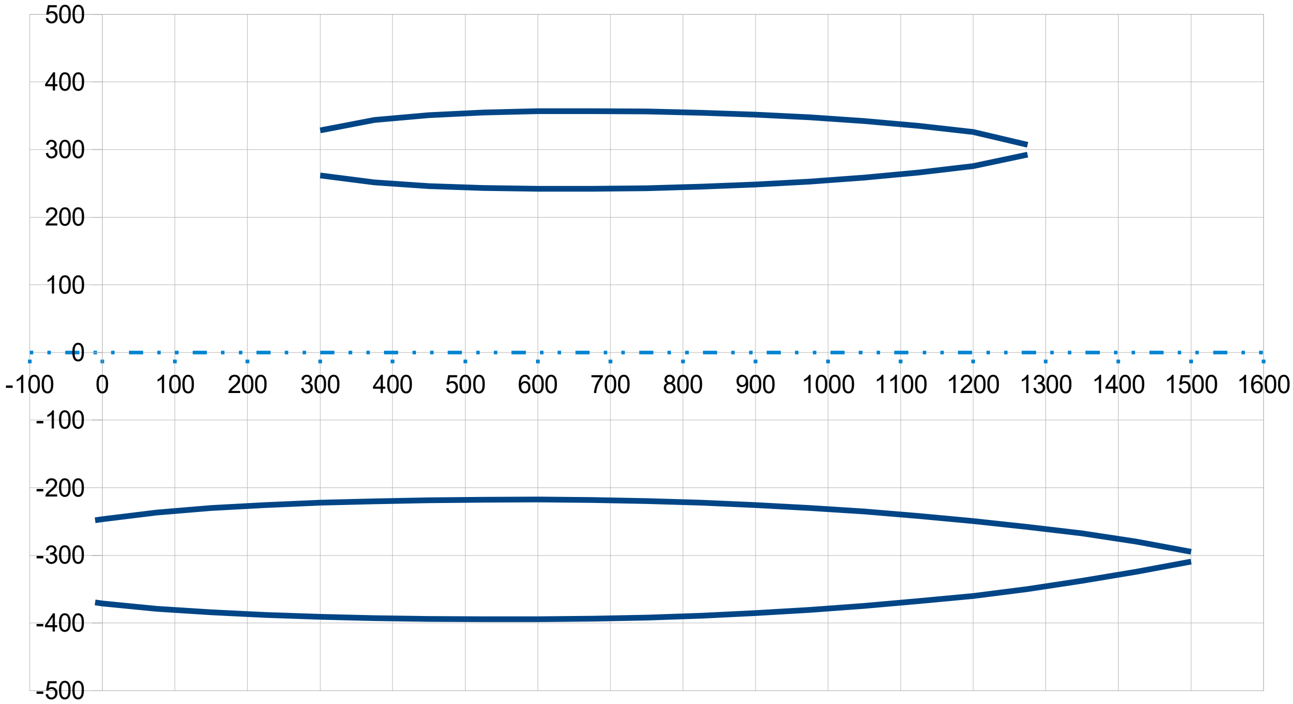
>>> Total Friction drag for the 2 hulls (+ daggerboard and rudder) : 2654 N

Comment : *at 12 knots for this 16 m catamaran with a moderate L/B, we are at the critical speed when wave drag is maximum, so the total wave drag is 6028 N to compare to 2654 N for the friction component, so a 69% / 31% proportion.*

Case 3 : 16m Cata assumed at speed of 18 knots with an heel angle of 7° - Input data		
S (Space between hull axis, m)	6,1	
	leeward hull 1	**windward hull 2**
Lw (m)	16,00	10,34
Bw (m)	1,77	1,15
Tc (m)	1,06	0,33
Displacement (N)	134096 (88%)	18210 (12%)
Cb	0,443	0,459
Cp	0,614	0,607
Hull wetted surface (m2)	35,52	11,09
Aft transom height (cm) (negative = immersion)	-22,4	50,8
>> Lw/Bw	9,04	8,98
>> Bw/Tc	1,66	3,47
For approach B >> Lw/D1/3	6,75	8,48

>> S/Lw	0,38	0,59
>> Fn	0,74	0,92





The leeward hull :

Residuary drag of the leeward hull as a monohull :

Approach A :
From Fig. 1A with Lw/Bw = 9,04 and Fn = 0,74 >>> Dr/Mg (%) ~ 4,6
From Fig. 2A with Bw/Tc = 1,66 and Fn = 0,74 >>> Correction factor ~ 1,1
A >>> Dr/Mg (Monohull) ~ 4,6 * 1,1 ~ **5,06**

Approach B :
From Fig. 1B with Lw/D^1/3 = 6,75 and Fn = 0,74 >>> Dr/Mg (%) ~ 5,48
B >>> Dr/Mg (%, Monohull) ~ 5,48

Residuary drag of the leeward hull as part of the catamaran, with S/Lw = 0,38 :
From Fig. 4 with Lw/Bw = 10,4 and Bw/Tc = 1,5 :
S/Lw = 0,38 and Fn = 0,74 >>> K ~ 0,11
From Fig. 7 with Lw/Bw = 12,8 and Bw/Tc = 1,5 :
S/Lw = 0,38 and Fn = 0,74 >>> K ~ 0,17
>>> So for Lw/Bw = 9,04 , by linear interpolation >>> K ~ 0,076

From Fig. 5 with Lw/Bw = 9 and Bw/Tc = 2,0 :
S/Lw = 0,38 and Fn = 0,74 >>> K ~ 0,21
From Fig. 8 with Lw/Bw = 11 and Bw/Tc = 2,0 :
S/Lw = 0,38 and Fn = 0,74 >>> K ~ 0,20
>>> So for Lw/Bw = 9,04 , by linear interpolation >>> K ~ 0,210

So finally for Bw/Tc = 1,66 >>> **K1** ~ 0,076 + (0,210-0,076)/(2,0-1,5)(1,66-1,5) **~ 0,119**

>>> Amplification factor = 1 + K1 (D2/D1) = 1 + 0,119 * (18210/134096) = **1,016**
>>> Residuary drag of the leeward hull, with using 5,48 from the approach B :
1,016 * (5,48/100) * 134096 **~ 7466 N**

<u>The windward hull :</u>

Residuary drag of the windward hull as a monohull :

Approach A :
From Fig. 1A with Lw/Bw = 8,98 and Fn = 0,92 >>> Dr/Mg (%) ~ 5,5
From Fig. 2A with Bw/Tc = 3,47 and Fn = 0,92 >>> Correction factor ~ 1,0
A >>> Dr/Mg (Monohull) ~ 5,5 * 1,0 **~ 5,5**

Approach B :
From Fig. 1B with Lw/D^1/3 = 8,48 and Fn = 0,92 >>> Dr/Mg (%) ~ 4,66
B >>> Dr/Mg (%, Monohull) ~ 4,66

Residuary drag of the windward hull as part of the catamaran, with S/Lw = 0,59 :

From Fig. 9 with Lw/Bw = 9 (# 8,98) and Bw/Tc = 2,5 :
S/Lw = 0,59 and Fn = 0,92 >>> K ~ 0,30
>>> by lack of data for Bw/Tc = 3,47 , + the fact that a priori, at constant Lw/Bw, a higher Bw/Tc gives less wave drag, so to be conservative we keep this value >>> **K2 ~ 0,30**

>>> amplification factor = 1 + K2 (D1/D2)^0,5 = 1 + 0,30 * (134096/18210)^0,5 ~ **1,81**

>>> Residuary drag of the leeward hull, with using 4,66 from the approach B :
1,81 * (4,66/100) * 18210 **~ 1536 N**

>>> Total Residuary drag = 7466 (leeward) + 1536 (windward) = 9002 N

Comparison with the friction drag of the hulls at 18 knots :

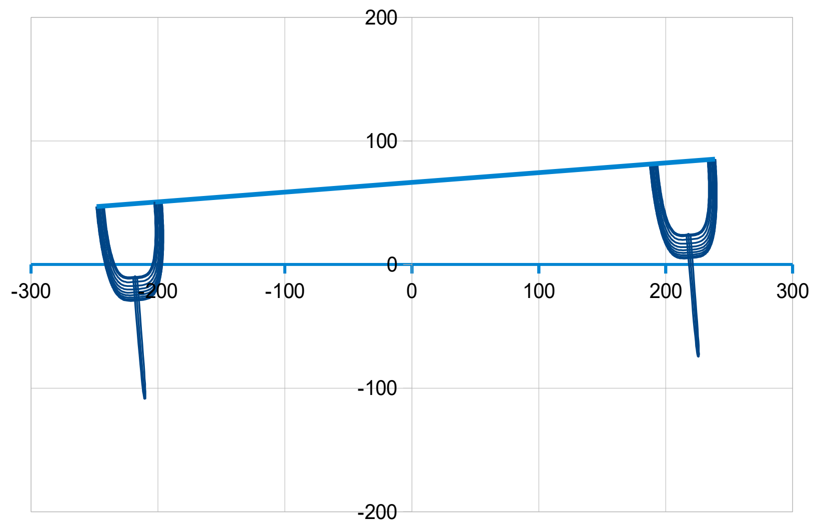
Leeward hull	**Windward hull**
Sw hull = 35,52 m2	Sw = 11,09 m2
Lw = 16 m	Lw = 10,34 m
Re (with using 0,7 Lw) = 1,04 E08	Re (with using 0,7 Lw) = 6,70 E07
Cf (ITTC 57) = 0,00207	Cf (ITTC 57) = 0,00221
>>> Df Hull = 3235 N	**>>> Df Hull= 1077 N**
Sw daggerboard = 2,39 m2	Sw daggerboard = 2,39 m2
Root chord = 0,7 m	Root chord = 0,7 m
Re (with using the root chord) = 6,48 E06	Re (with using the root chord) = 6,48 E06
Cf (ITTC 57) = 0,00324	Cf (ITTC 57) = 0,00324
>>> Df daggerboard = 340 N	**>>> Df daggerboard = 340 N**
Sw rudder = 1,15 m2	Sw rudder ~ 0,75 m2 (not fully immerged)
Root chord = 0,4 m	Root chord = 0,4 m
Re (with using the root chord) = 3,70 E06	Re (with using the root chord) = 3,70 E06
Cf (ITTC 57) = 0,00359	Cf (ITTC 57) = 0,00359
>>> Df rudder = 181 N	**>>> Df rudder = 118 N**
>>> Df leeward = 3756 N	>>> Df windward = 1535 N

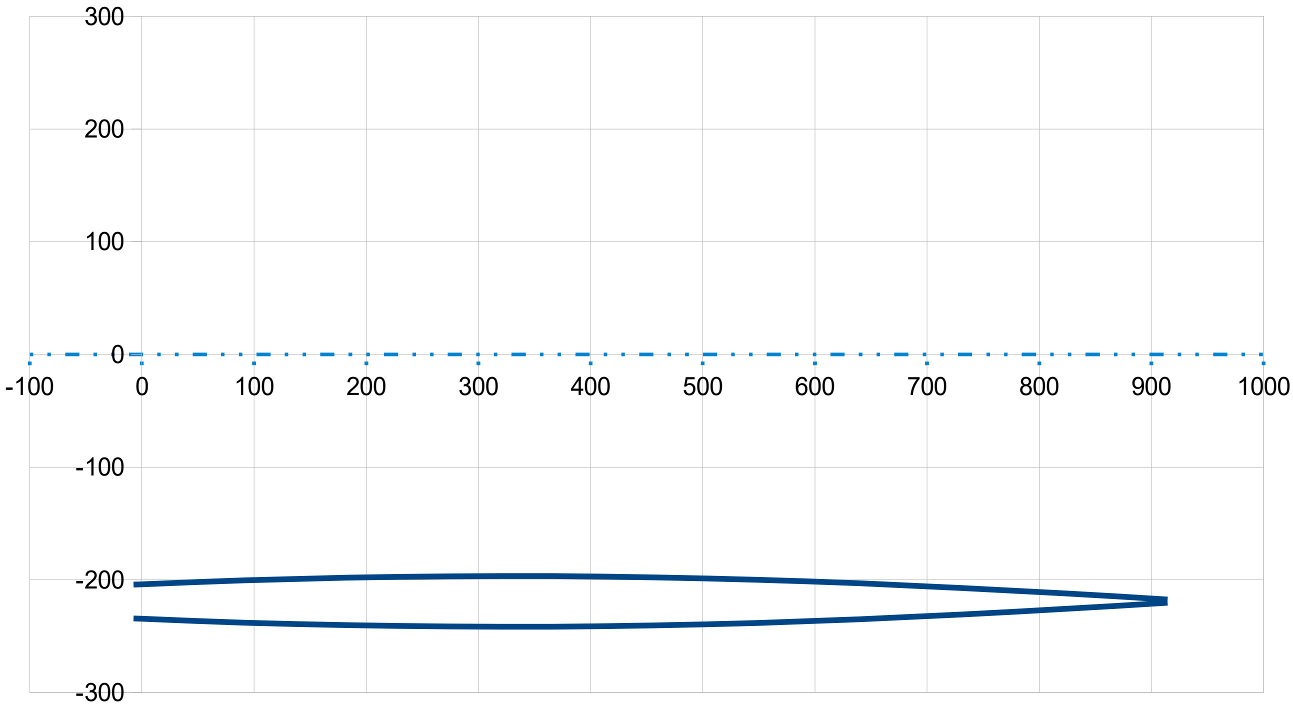
>>> Total Friction drag for the 2 hulls (+ daggerboard and rudder) : 5291 N

Comment : *at 18 knots for this 16 m catamaran with a moderate L/B (~ 9,7 when upright), the wave drag is 9002 N while 5291 N for the friction drag, so a 63% / 37% proportion.*

Case 4 : 9m racing Cata assumed at speed of 12 knots with an heel angle of 4°5 - Input data		
S (Space between hull axis, m)	6,1	
	leeward hull 1	**windward hull 2 is flying over the water**
Lw (m)	9,54	-
Bw (m)	0,45	-
Tc (m)	0,31	-
Hull displacement (N)	6514 (100%)	0,00%
Cb	0,481	-
Cp	0,634	-
Hull wetted surface (m2)	6,42	-
Aft transom height (cm) (negative = immersion)	-9,7	-
>> Lw/Bw	21,25	-
>> Bw/Tc	1,43	-
For approach B >> Lw/D1/3	11,03	
>> S/Lw	0,64	-
>> Fn	0,64	-

Comment : *in that case, the ratios are outside the ranges of validity : Cb = 0,48 instead of around 0,4 ; Lw/Bw is 21,25 outside (7 to 15) ; Bw/Tc 1,43 a bit outside (1,5 to 2,5) ; Lw/D^1/3 is 11,03, outside (6,27, 9,5)*





<u>The leeward hull :</u>

Residuary drag of the leeward hull as a monohull :

Approach A :

Here, by default, and being a priori conservative, we assume the residuary drag coefficient for Lw/Bw = 15 with Cb 0,4, instead of the real value Lw/Bw 21,25 with a Cb 0,48

From Fig. 1A with Lw/Bw ~ 15 and Fn = 0,64 >>> Dr/Mg (%) ~ 2,7

From Fig. 2A with Bw/Tc = 1,43 and Fn = 0,64 >>> Correction factor ~ 1,22

A >>> Dr/Mg (Monohull) ~ 2,7 * 1,22 **~ 3,3**

Approach B :

Here, by default, as 11,03 is not far from 9,5, we estimate the residuary drag coefficient by linear interpolation between 8,5 and 9,5 for Lw/D^1/3

From Fig. 1B with Lw/D^1/3 = 11,03 and Fn = 0,64 >>> Dr/Mg (%) ~ 2,86

B >>> Dr/Mg (%, Monohull) ~ 2,86

No interference factor as the windward hull is full flying >>> K1 = 0

>>> Residuary drag of the leeward hull, with using 2,86 from the approach B :

1,0 * (2,86/100) * 6514 **~ 186 N**

<u>The windward hull :</u> full flying >>> no residuary drag of the hull

>>> Total Residuary drag = 186 (leeward) + 0 (windward) = 186 N

Comparison with the friction drag of the hulls at 12 knots :

Leeward hull	**Windward hull**
Sw hull = 6,42 m2	Sw = 0 m2
Lw = 9,54 m	-
Re (with using 0,7 Lw) = 4,12 E07	-
Cf (ITTC 57) = 0,00238	-
>>> Df Hull = 298 N	-
Sw daggerboard = 0,76m2	Sw daggerboard = 0,76m2
Root chord = 0,35 m	Root chord = 0,35 m
Re (with using the root chord) = 2,16 E06	Re (with using the root chord) = 2,16 E06
Cf (ITTC 57) = 0,00399	Cf (ITTC 57) = 0,00399
>>> Df daggerboard = 59 N	**>>> Df daggerboard = 59 N**
Sw rudder = 0,45 m2	Sw rudder ~ 0,34 m2 (not fully immerged)
Root chord = 0,25 m	Root chord = 0,25 m
Re (with using the root chord) = 1,54 E06	Re (with using the root chord) = 1,54 E06
Cf (ITTC 57) = 0,00428	Cf (ITTC 57) = 0,00428
>>> Df rudder = 38 N	**>>> Df rudder = 29 N**
>>> Df leeward = 395 N	>>> Df windward = 88 N

>>> Total Friction drag for the 2 hulls (+ daggerboard and rudder) : 483 N

Comment : *at 12 knots for this 9 m racing catamaran with a high L/B (~ 22,7 when upright), the wave drag is 186 N while it is 483 N for the friction drag, so a 28% / 72% proportion.*

Sum-up of the 2 approaches A and B for the Dr/Mg monohull

	Dr/Mg (%)	Approach A using Fig. 1A & 2A (Lw/Bw + correction Bw/Tc)	Approach B using Fig. 1B (Lw/D^1/3)
Case 1	Leeward hull	0,85	0,85
	Windward hull	0,90	0,90
Case 2	Leeward hull	3,70	3,49
	Windward hull	3,57	3,33
Case 3	Leeward hull	5,06	5,48
	Windward hull	5,50	4,66
Case 4	Leeward hull	3,30	2,86
	Windward hull	-	-