Teksen AYGOR

6th EMship cycle: October 2015 – February 2017

Master Thesis

Analyses of Foil Configurations of IMOCA Open 60s with Towing Tank Test Results

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Szczecin, January 2017

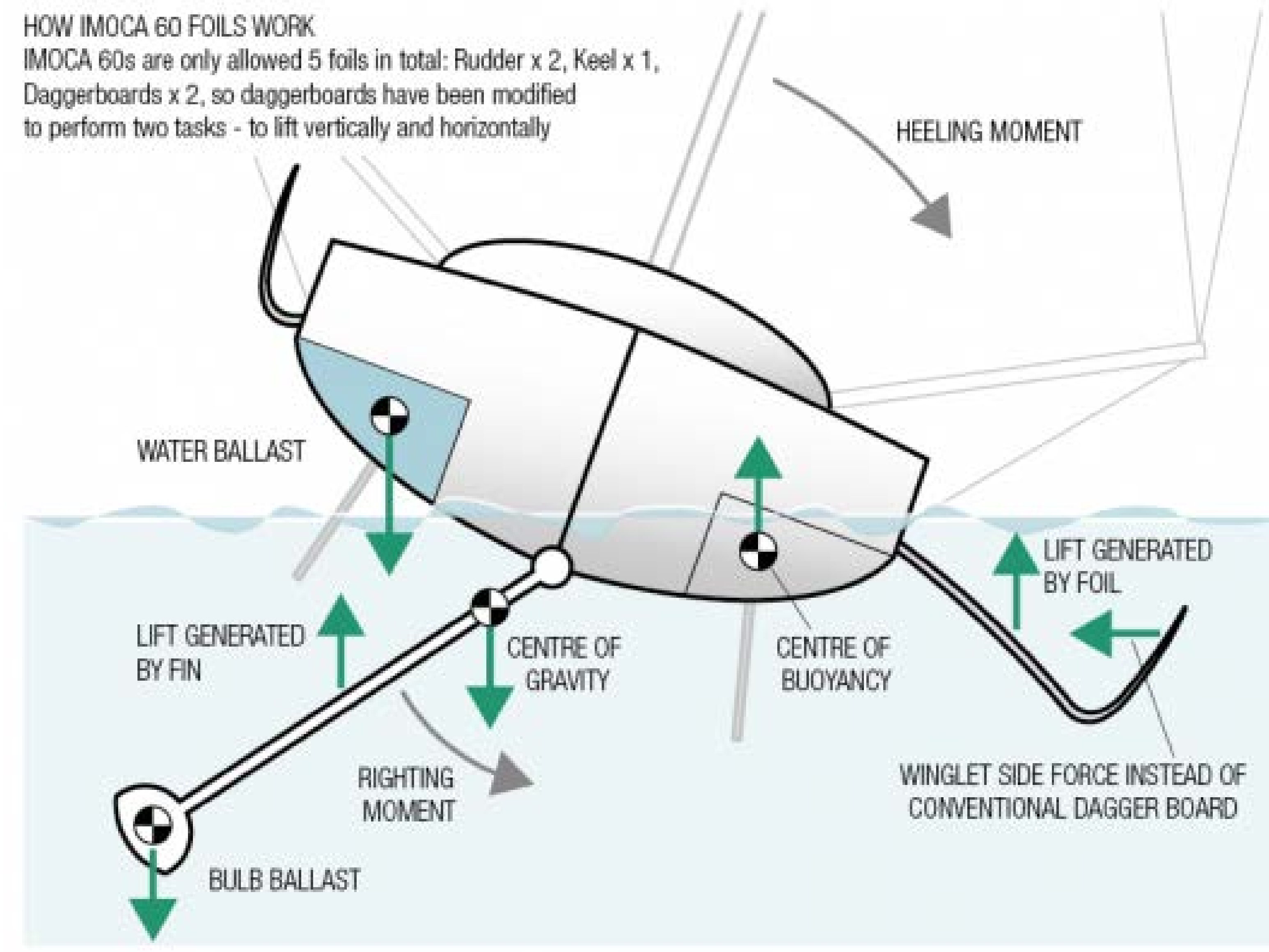
Contents

Aims and Objectives

- Form Factor values were determined at some heel angles for resistance calculations
- The uncertainty analysis was performed to get the amount of the general uncertainy value during the experimental tests.
- 0° and 40° canting keel situations were evaluated with righting arm and effective draft results.
- Drag, Side Force and Lift values were obtained from towing tank tests with the 1/2 and Full sizes of two different foil configurations separately in upwind conditions.
- These effective draft and Lift results were considered in comparison of two different foil configurations and these obtained values were analyzed to get critical results in the upwind condition.

Vendée Globe

- Solo Race
- Non-stop
- Without Assistance
- Around the World
- The International Monohull Open Class Association (IMOCA)
- The World Sailing (or formerly International Sailing Federation-ISAF)
- Skippers, Sponsors, Teams (Designers & Engineers)
- IMOCA Open 60 Sailboats

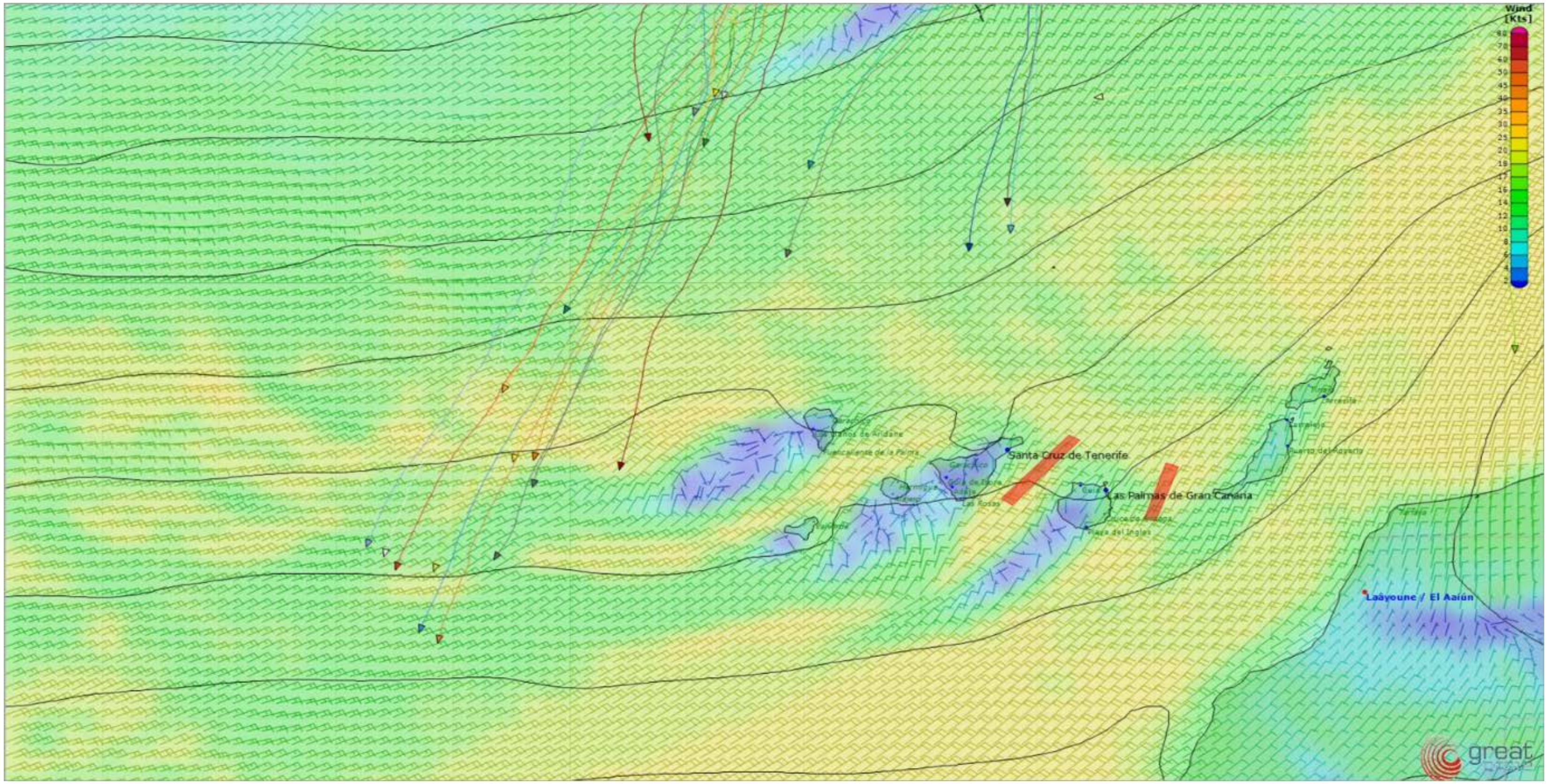

HOW IMOCA 60 FOILS WORK
IMOCA 60s are only allowed 5 foils in total: Rudder x 2, Keel x 1, Daggerboards x 2, so daggerboards have been modified to perform two tasks - to lift vertically and horizontally
HEELING MOMENT
WATER BALLAST
LIFT GENERATED BY FOIL
LIFT GENERATED BY FIN
CENTRE OF GRAVITY
CENTRE OF BUOYANCY
RIGHTING MOMENT
WINGLET SIDE FORCE INSTEAD OF CONVENTIONAL DAGGER BOARD
BULB BALLAST

The Vendée Globe Route

Location	Wind Speed-[m/s]	Wind Speed-[knots]	Sailing Conditions	Wave Heights-[m]	Beaufort Scale
1	7	14	Running	1,75	4
2	8	16	Broad Reach	2	5
3	10	19	Close Hauled	2,75	5
4	11	21	Close Hauled	3	5
5	6	12	Close Hauled	1,5	4
6	9	18	Running	2,7	5
7	9	18	Running	2,7	5
8	10	19	Running	2,75	5
9	8	16	Running	2	5
10	7	14	Broad Reach	1,75	4
11	9	18	Running	2,7	5
12	4	8	Running	0,7	3
13	5	10	Close Hauled	0,8	3
14	10	19	Close Reach	2,75	5
15	14	27	Running	4	7

Satellite View Around the Canary Islands

- %20-25 → Upwind Conditions
- %80 → Downwind Conditions



SOUTHAMPTON SOLENT UNIVERSITY

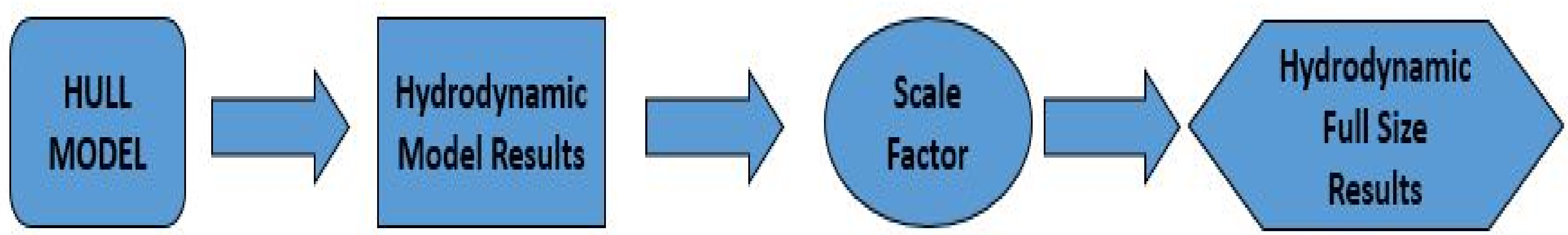
- Towing Tank Facility

General Modelling Laws & Methodology

- **Geometrical, Kinematic and Dynamic Similarities**

$$\textbf{Scale Factor} - \lambda = \frac{Ship\ Length}{Model\ Length}$$

$$Fr(m) = \frac{U(m)}{\sqrt{g \cdot l(m)}} = \quad Fr(s) = \frac{U(s)}{\sqrt{g \cdot l(s)}} \rightarrow U(m) = U(s) \cdot \sqrt{\frac{g \cdot l(m)}{g \cdot l(s)}} = \frac{U(s)}{\sqrt{\lambda}}$$



ITTC Recommended Procedures and Guidelines

$$Cwave(model)(Fr) = Cwave(ship)(Fr)$$
$$Ct(Re, Fr) = (1 + k)Cf(Re) + Cw(Fr)$$

Prohaska's Method – Form Factors

$$\frac{Ct}{Cf} = (1 + k) + b * \frac{Fr^4}{Cf}$$

$0.1 \leq$ Froude Number ≤ 0.2

Form Factor Values - (1+k) For Sailing States	
Upright Condition	1,32
10° Heel Angle	1,26
15° Heel Angle	1,19
20° Heel Angle	1,13
25° Heel Angle	1,12

Uncertainty Analysis

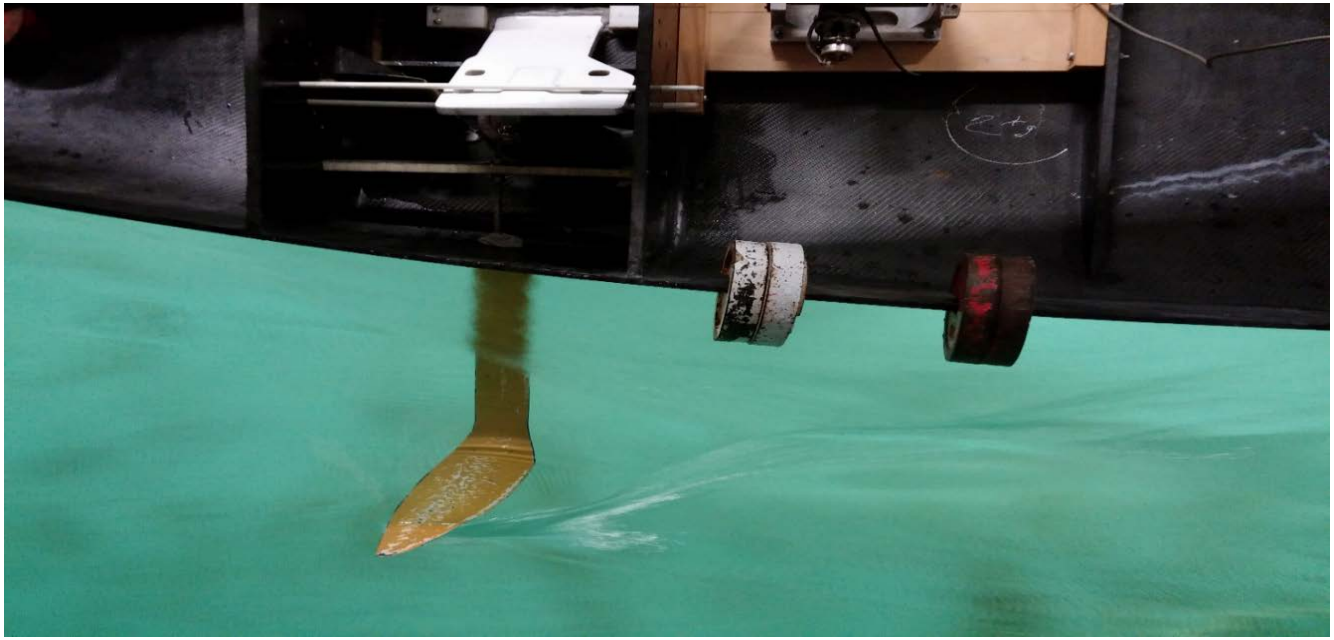
Main Parameters		
Average Temperature	19,5	°C
Fresh Water Density	998,31	kg/m³
Fresh Water Viscosity-ν	1,02E-06	m²/sn
Model Waterline Length-LWL	2,25	m
Model Length Overall Submerged-LOS	2,286	m
Wetted Surface Area	0,88	m²
Model Speed	1,613	m/s
Froude Number	0,34	-
Reynolds Number	3,63E+06	-
Coefficient of Frictional Resistance-Cf	3,61E-03	-
Total Resistance-Rt	6,18	N
Coefficient of Total Resistance-Ct	5,40E-03	-
Form Factor- (1+k)	1,32	-
Coefficient of Residuary Resistance-CR	6,42E-04	-

Total Uncertainties		
Temperature	0,5	%
Fresh Water Density	3,02E-03	%
Fresh Water Viscosity	1,1	%
Model Waterline Length-LWL	0,1	%
Model Length Overall Submerged-LOS	0,1	%
Wetted Surface Area	0,1	%
Model Speed	0,1	%
Froude Number	0,2	%
Reynolds Number	0,3	%
Coefficient of Frictional Resistance-Cf	0,1	%
Total Resistance-Rt	0,3	%
Coefficient of Total Resistance-Ct	0,5	%
Form Factor - k	3	%
Coefficient of Residuary Resistance-CR	4	%

The Sailing Yacht Resistance

- **Upright Resistance (consisting of frictional and wave making resistances)**
- **Heel Resistance (when the boat is heeled, it will contain the resistance components due to the heeling)**
- **Induced Resistance (the drag due to total side force generated by hull/appendages – associated with Froude number)**

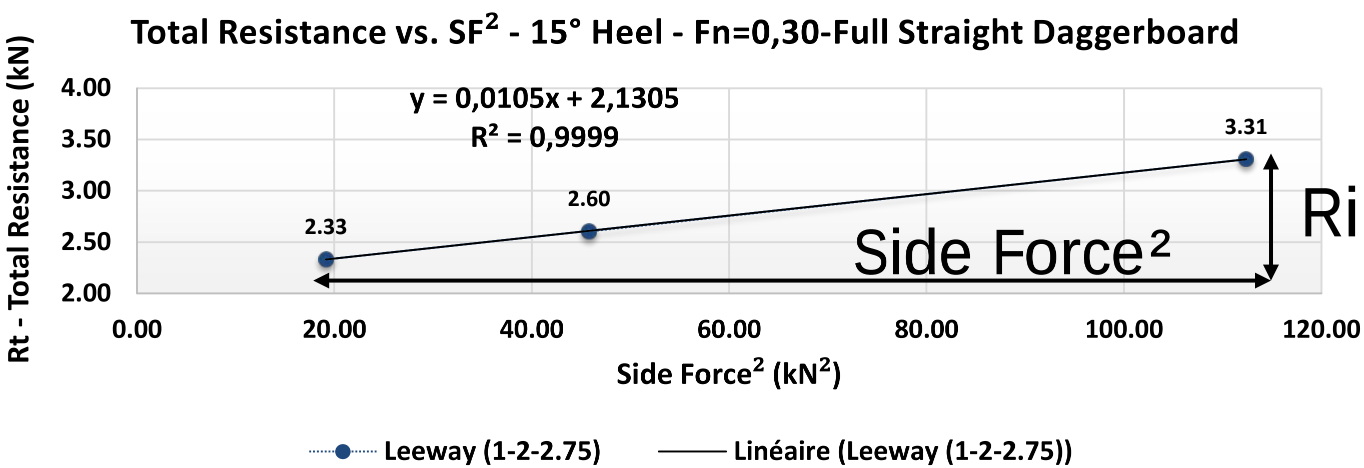
$$Rtotal = Rupright + Rheel + Rinduced$$



Effective Draft Method

Keel Position	DBD Position	% DBD	Heel	Leeway	Clock No	V-Full Size (m/s)	FN	Full Size Total-Rt (kN)	SF^2 (kN)	Ri (kN)
40°	Full DBD	100	15°	1°	350	4,0	0,30	2,33	19,14	0,20
40°	Full DBD	100	15°	2°	350	4,0	0,30	2,60	45,80	0,48
40°	Full DBD	100	15°	2,75°	350	4,0	0,30	3,31	112,38	1,18

Ru+Rh (kN)	Slope	Te^2	Te (m)
2,13	0,0105	1,86	1,36

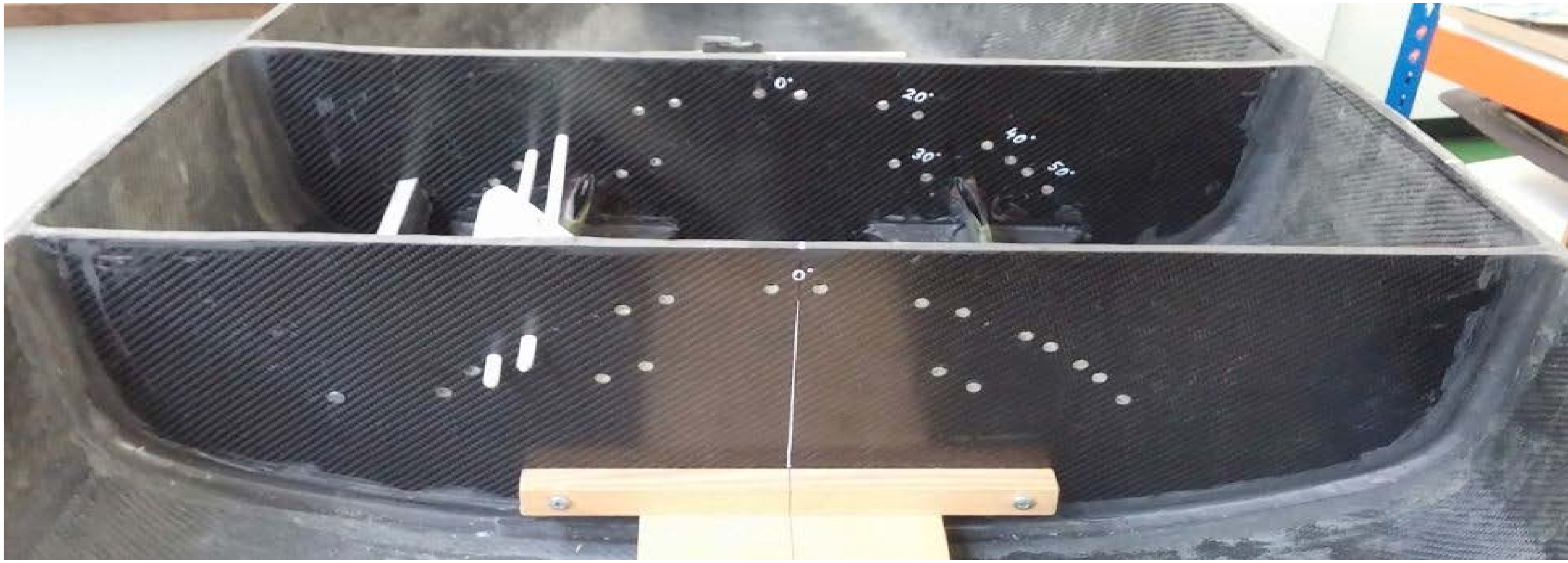


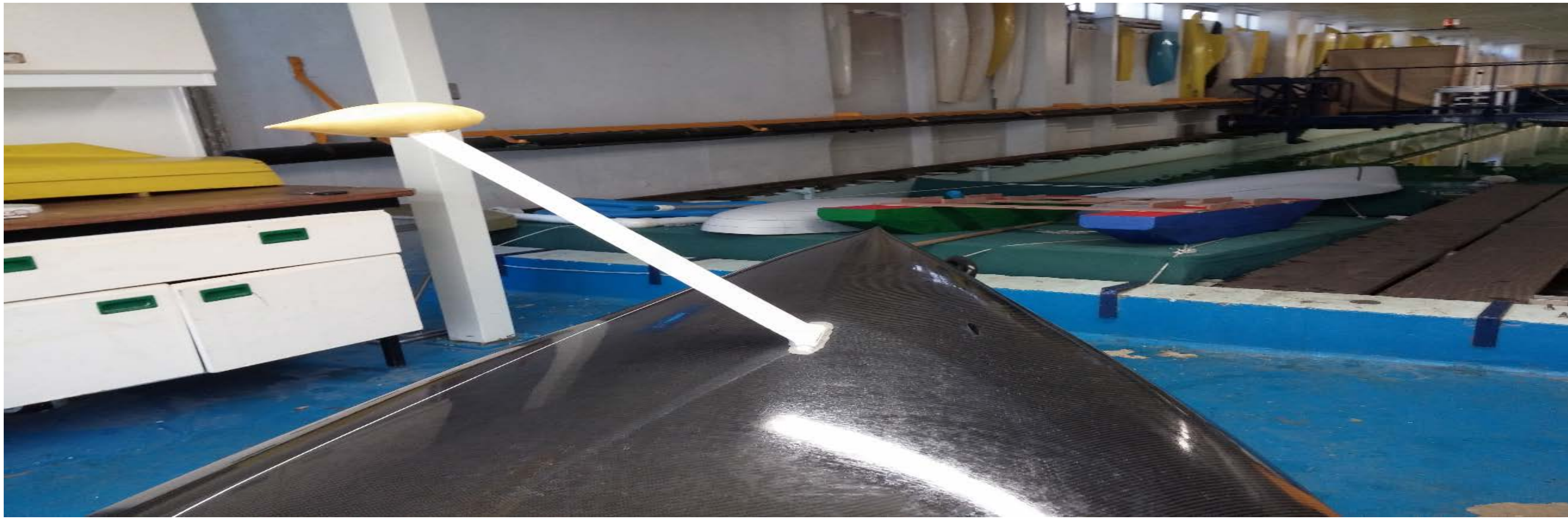
$$Slope \quad \frac{y}{x} = \frac{Induced\ Drag}{(Side\ Force^2)} = \frac{1}{T_e^{\,2} \cdot \pi \cdot \rho \cdot V^2}$$

Full Size Dimensions

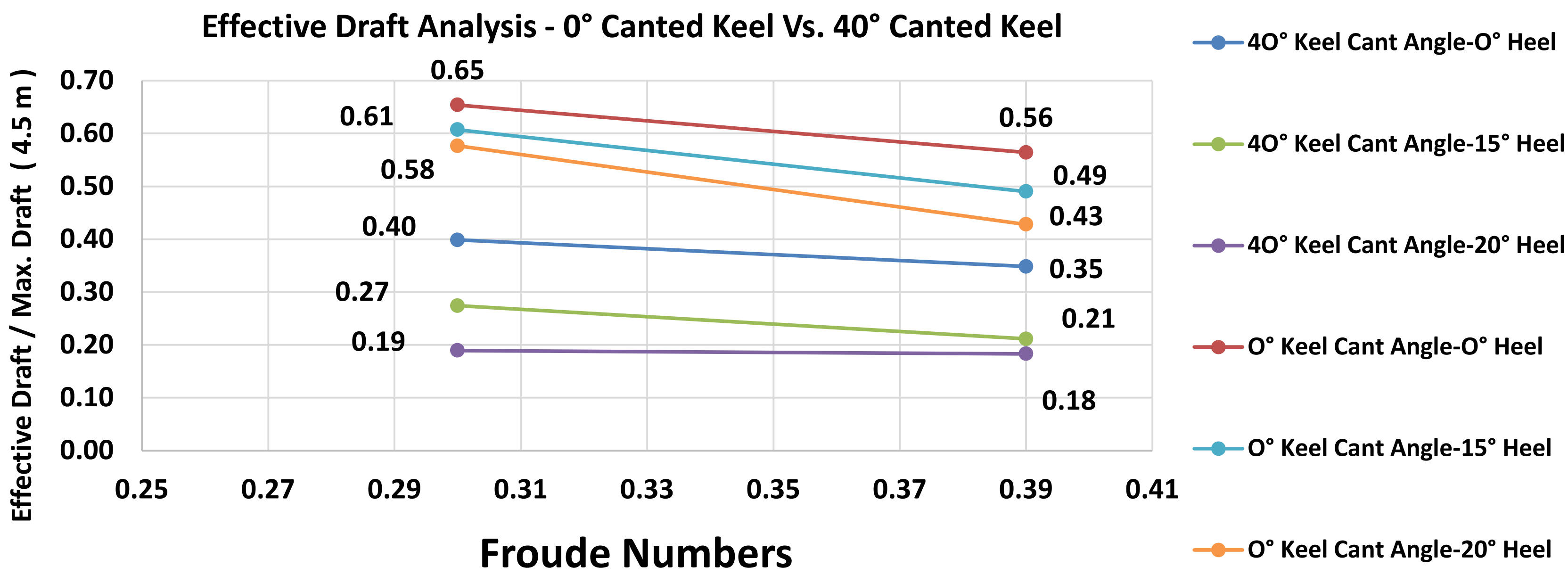
Keel		Rudder		Bulb		Units
Chord	0,66	Chord	0,24	Chord	3,20	m
Span	3,68	Span	1,2	Span	-	m
WSA	4,83	WSA	0,58	WSA	3,07	m²
t/c	0,1	t/c	0,1	t/c	0,15	-
(1+k)	1,21	(1+k)	1,21	(1+k)	1,23	-

0° and 40° Canting Keel Analysis





0° and 40° Canting Keel Analysis

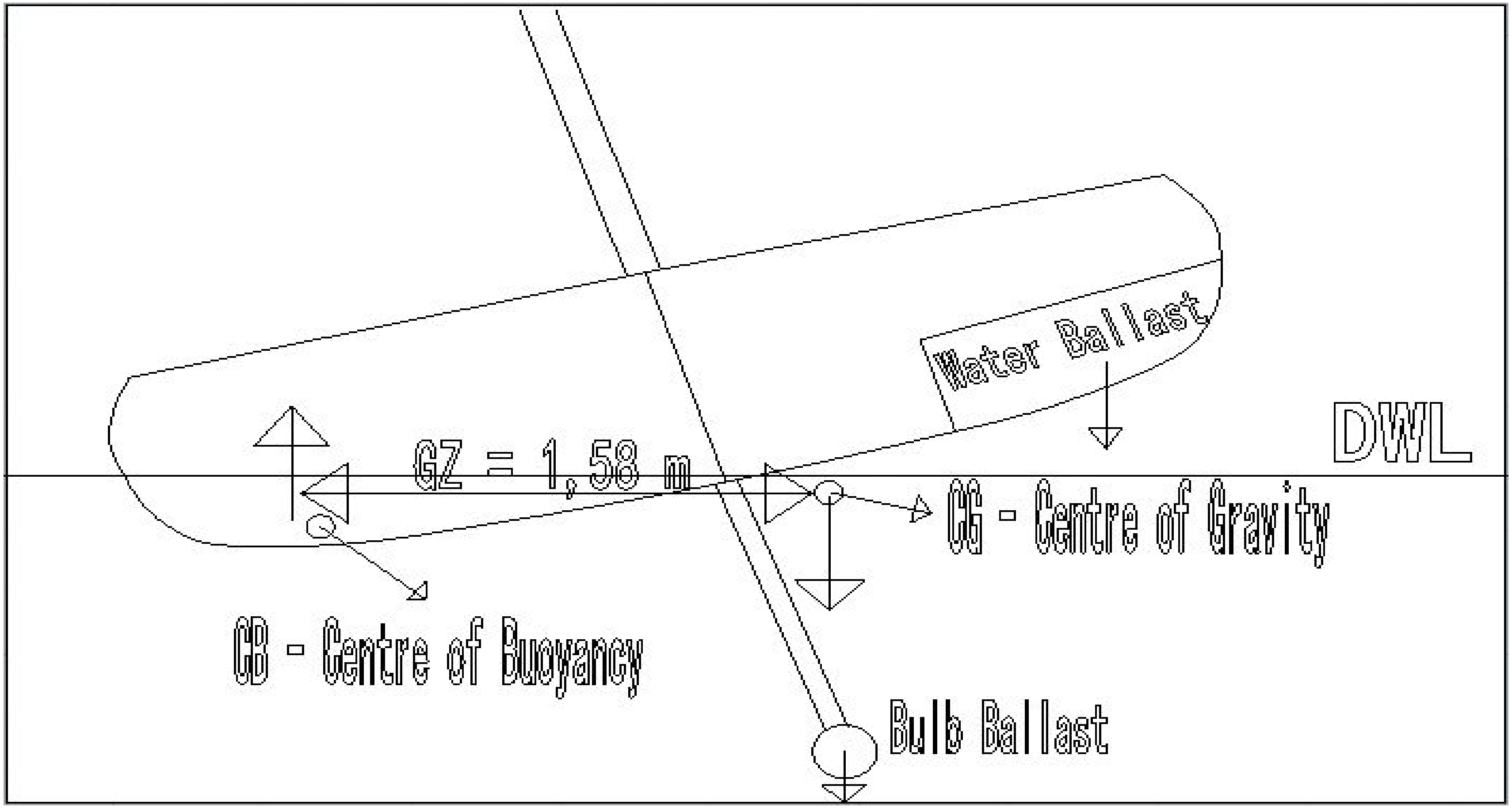


The Effective Draft Results of 4O° Canted Keel		
Conditions	Fn	
	0,30	0,39
4O° Cant Angle-O° Heel	1,79	1,57
4O° Cant Angle-10° Heel	1,26	1,14
4O° Cant Angle-15° Heel	1,23	0,95
4O° Cant Angle-20° Heel	0,85	0,82
4O° Cant Angle-25° Heel	0,55	0,61

Effective Draft Results of O° Canted Keel		
Conditions	Fn	
	0,3	0,4
O° Cant - O° Heel Angle	2,94	2,54
O° Cant - 15° Heel Angle	2,73	2,21
O° Cant - 20° Heel Angle	2,59	1,93

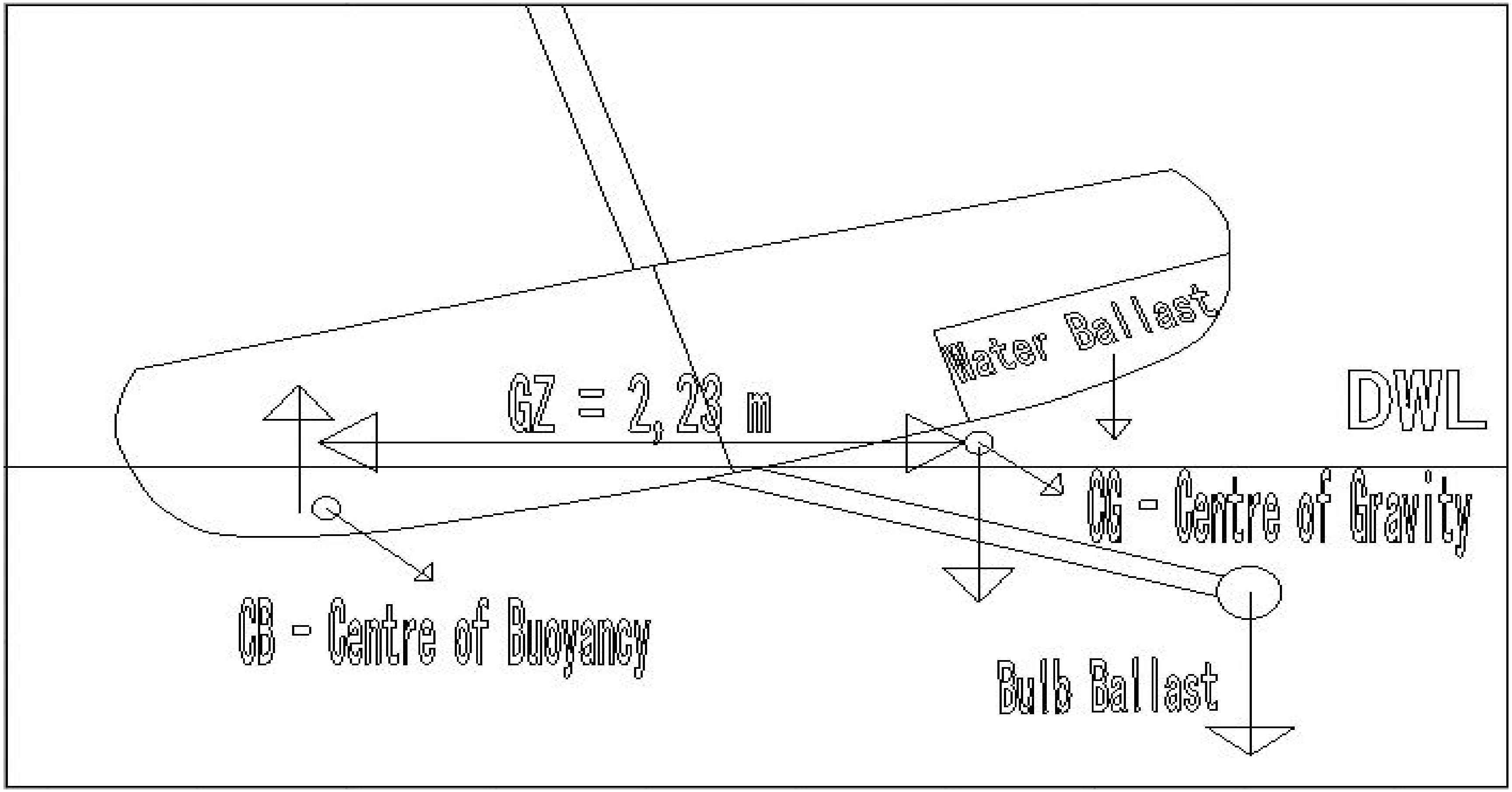
0° Canted Keel+Water Ballast					
Heel Angle	Displacement (kg)	GZ (m)	HA (m)	RM (kg.m)	FH-N
15°	9260	1,58	16,6	14594	8330

GZ= Righting Arm - HA=Heeling Arm- RM=Righting (Heeling) Moment – FH= Heel Force



40° Canted Keel+Water Ballast					
Heel Angle	Displacement (kg)	GZ (m)	HA (m)	RM (kg.m)	FH-N
15°	6544	2,23	16,6	14594	8330

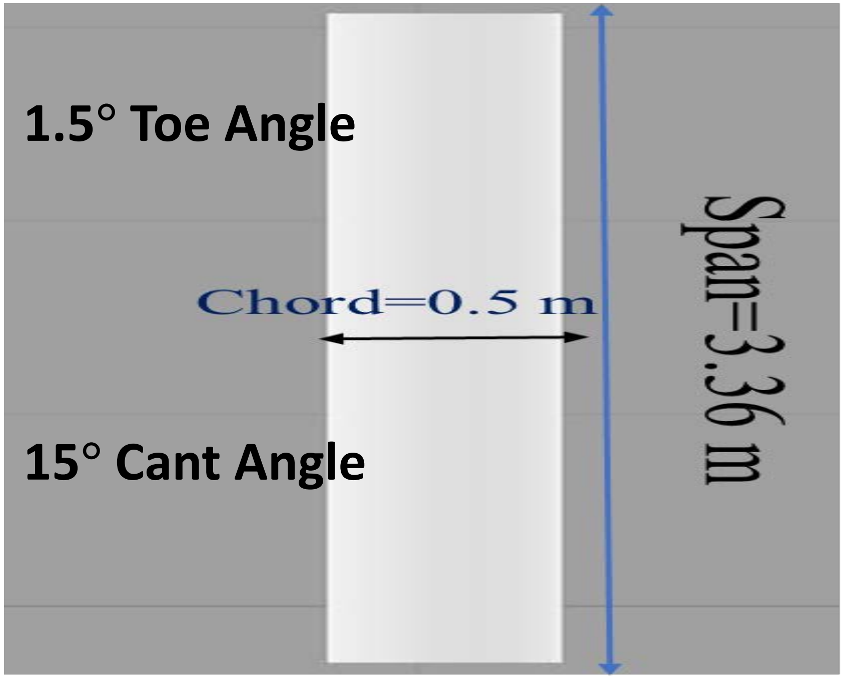
GZ= Righting Arm - HA=Heeling Arm- RM=Righting (Heeling) Moment – FH= Heel Force

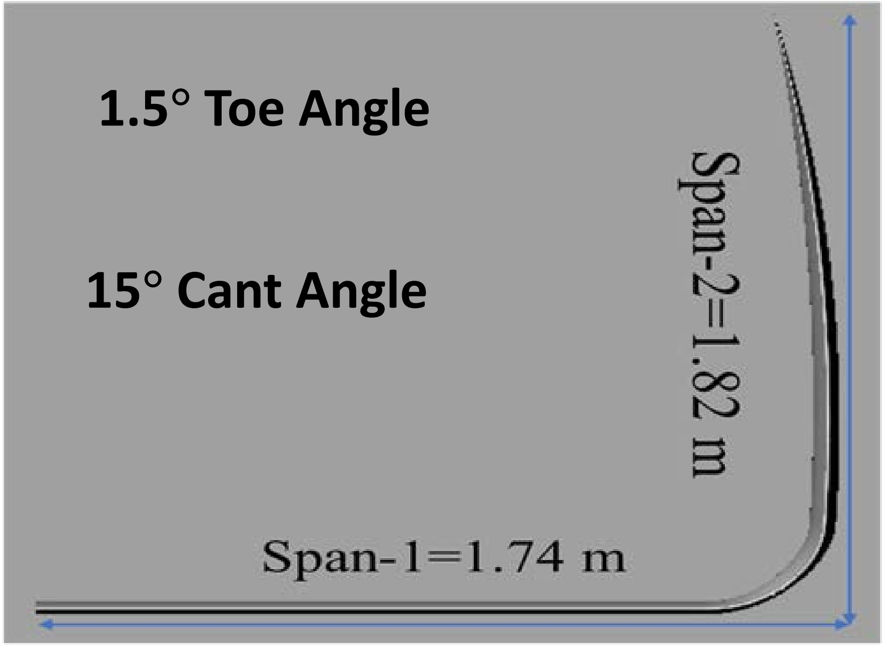


1/2 & Full - Straight & Curved Daggerboards

Full Scale Full Straight Foil	
Chord (m)	0,50
Span (m)	3,36
WSA (m²)	3,39
t/c	0,1
(1+k)	1,21
Full Scale 1/2 Straight Foil	
Span (m)	1,68

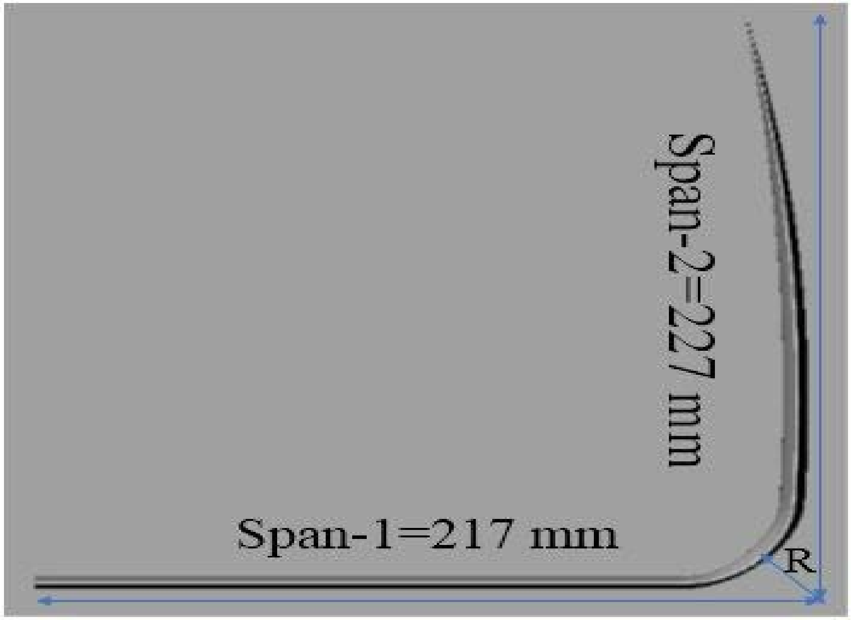
Full Scale Full Curved Foil	
Chord1 (m)	0,38
Span1 (m)	1,74
Chord2 (m)	0,57
Span2 (m)	1,82
Avg Chord	0,47
WSA (m²)	3,37
t/c	0,12
(1+k)	1,25
Full Scale 1/2 Curved Foil	
Span1 (m)	0,87





Curved Daggerboard Design

Approximate Specifications of Representative Curved Foil				
Model Average Values				
Chord1	0,047	m	47	mm
Span1	0,217	m	217	mm
Chord2	0,071	m	71	mm
Span2	0,227	m	227	mm
Radius-R	0,041	m	41	mm
Location from aft	1,12	m	1119	mm
Naca Section NACA 63-412 was used for the foils				



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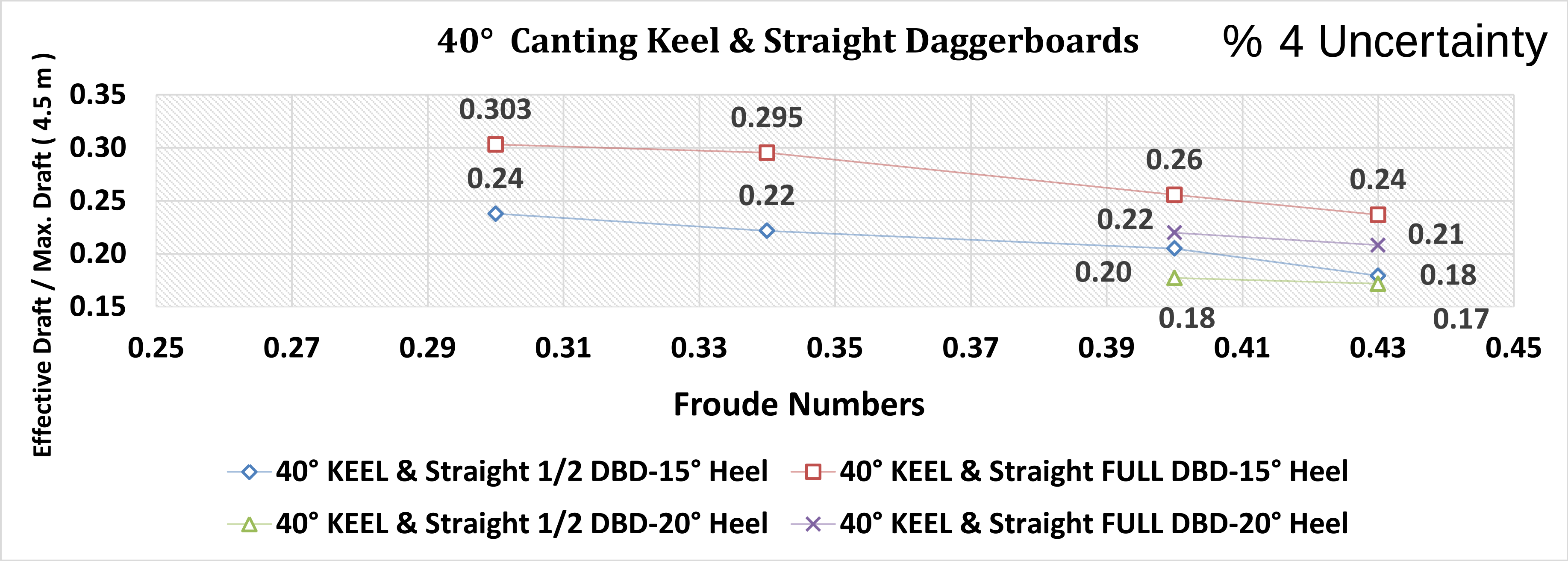
- Composite Workshop & 3D Printer

Straight Daggerboard Configurations & 40° Canting Keel

- **It is a retractable daggerboard design**
- **The 1/2 & Full Straight Foil Configurations**
- **40° Canting Keel**

Straight Daggerboard Configurations & 40° Canting Keel

Full Size Effective Draft Table For Straight Daggerboard Configurations				
Froude Numbers	15° Heel Angle & 1/2 Straight Foil (m)	15° Heel Angle & Full Straight Foil (m)	20° Heel Angle & 1/2 Straight Foil (m)	20° Heel Angle & Full Straight Foil (m)
0,3 (4 m/s)	1,07	1,36	-	-
0,34	1,00	1,25	-	-
0,4 (5.13 m/s)	0,92	1,11	0,78	0,99
0,43	0,81	1,01	0,77	0,94



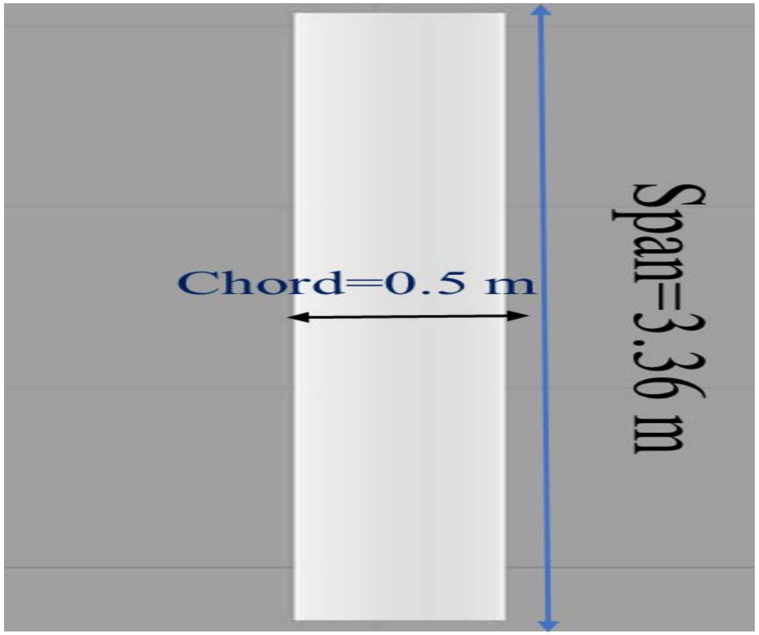
1/2 & Full Straight Daggerboard Configurations & 40° Canting Keel

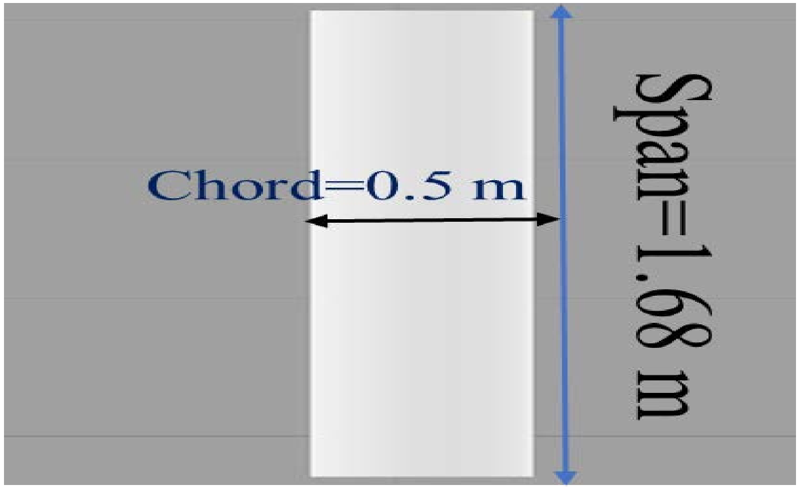
$AR = \frac{b}{c} \rightarrow \downarrow Cdi = \frac{Cl^2}{\pi . AR} \uparrow$ where b=Span & c=Chord

$Lift = \frac{1}{2} \rho V^2 S\, Cl$ – S =Foil Area (m²)

Full Size - Effective Draft Values at 15° Heel Angle	
Froude Number - (4 m/s)	0,30
Full Straight Foil & 40° Canting Keel (m)	1,36
Only 40° Canting Keel (m)	1,23
1/2 Straight Foil & 40° Canting Keel (m)	1,07

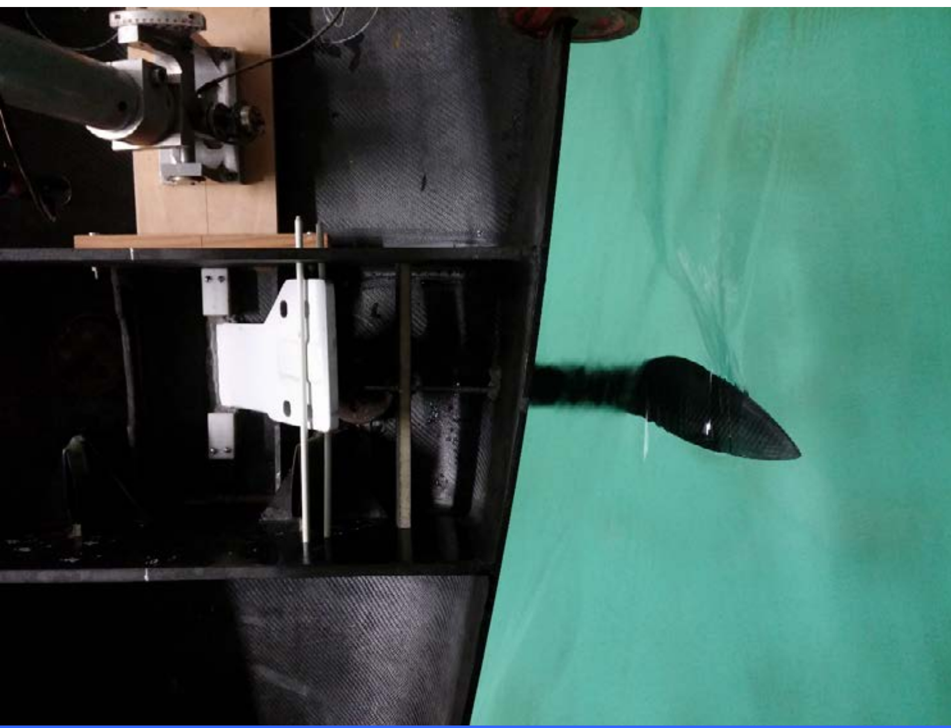
Full Size - Heave Analysis Values of 1/2 -Full Straight Foils	
20° Heel Angle & 0.40 Froude Number (5.13 m/s)	
Better Configuration - Full Straight Foil	
Lift Difference (mm)	2,60
Water Plane Area- 20° Heel (m²)	36,04
Lift Force Difference (kN)	0,94
Displacement Difference (tonnes)	0,10

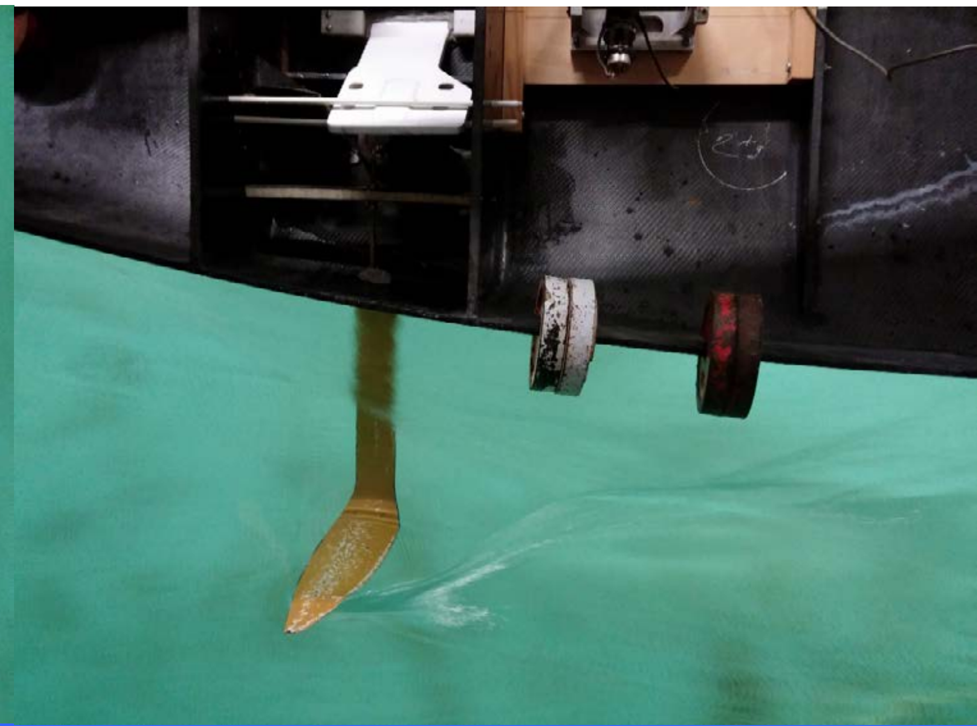




Curved Daggerboard Configurations & 40° Canting Keel

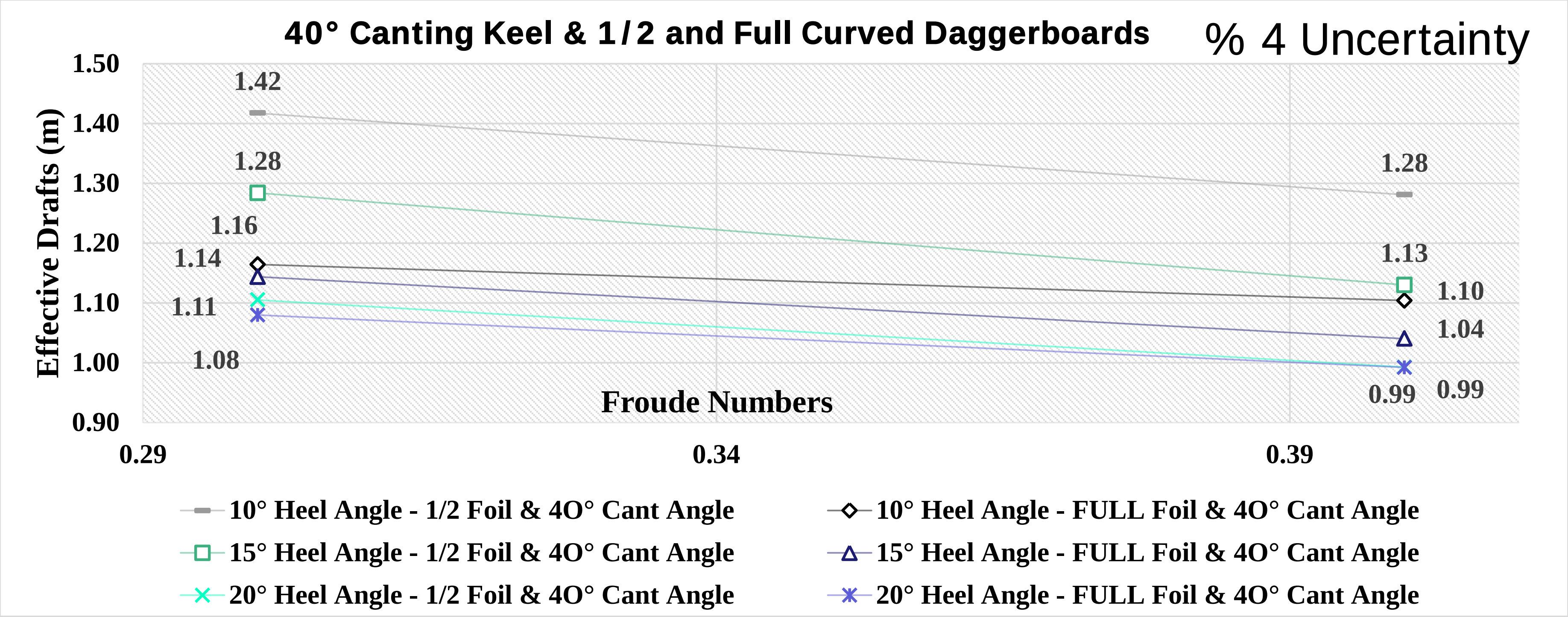
- The 1/2 & Full Curved Foil Configurations
- 40° Canting Keel
- 15° Cant Angle For Foils
- 1.5° Angle of Attack For Both Parts of Foils

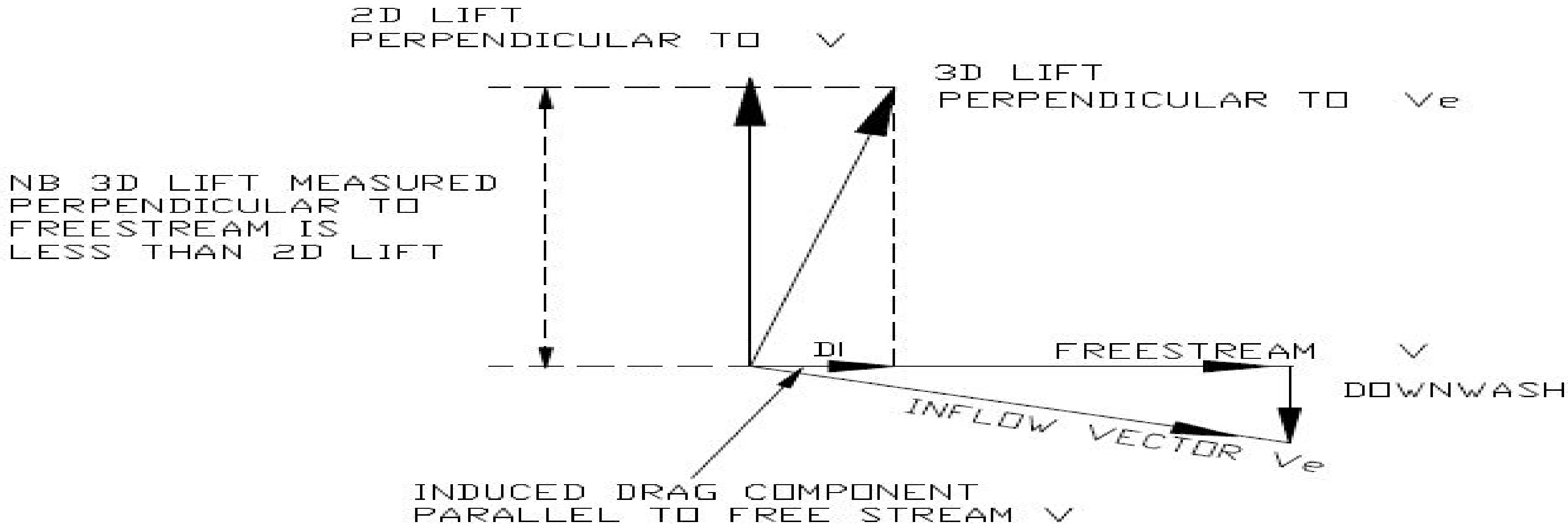




Curved Daggerboard Configurations & 40° Canting Keel

Full Size - Effective Draft Results of 1/2 & Full Curved Foils		
Sailing Conditions	Froude Numbers	
	0,3 - (4 m/s)	0,4 (5.13 m/s)
10° Heel Angle & 1/2 -Curved Foil (m)	1,42	1,28
15° Heel Angle & 1/2 - Curved Foil (m)	1,28	1,13
20° Heel Angle & 1/2 - Curved Foil (m)	1,11	0,99
10° Heel Angle & Full - Curved Foil (m)	1,16	1,10
15° Heel Angle & Full - Curved Foil (m)	1,14	1,04
20° Heel Angle & Full – Curved Foil (m)	1,08	0,99




2D LIFT
PERPENDICULAR TO V
3D LIFT
PERPENDICULAR TO Ve
NB 3D LIFT MEASURED
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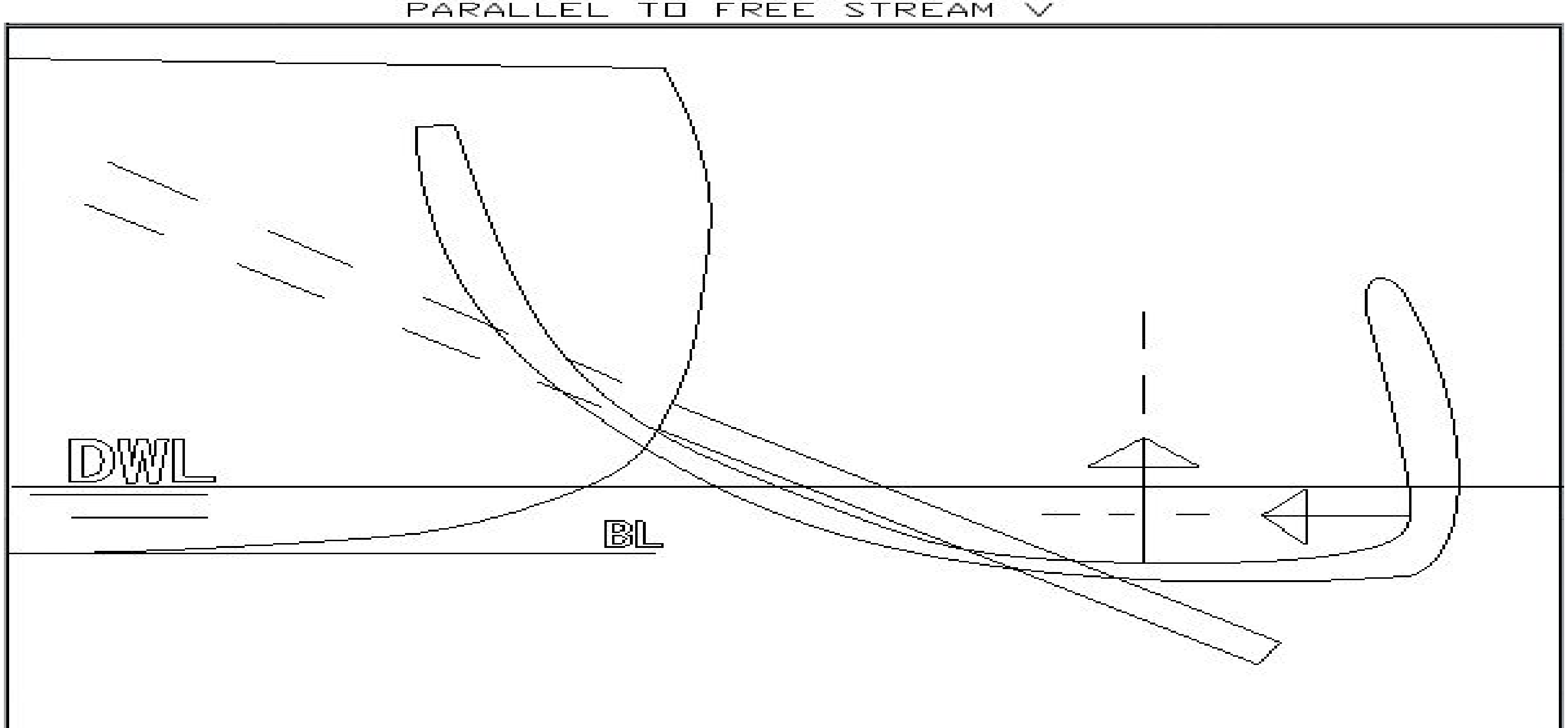
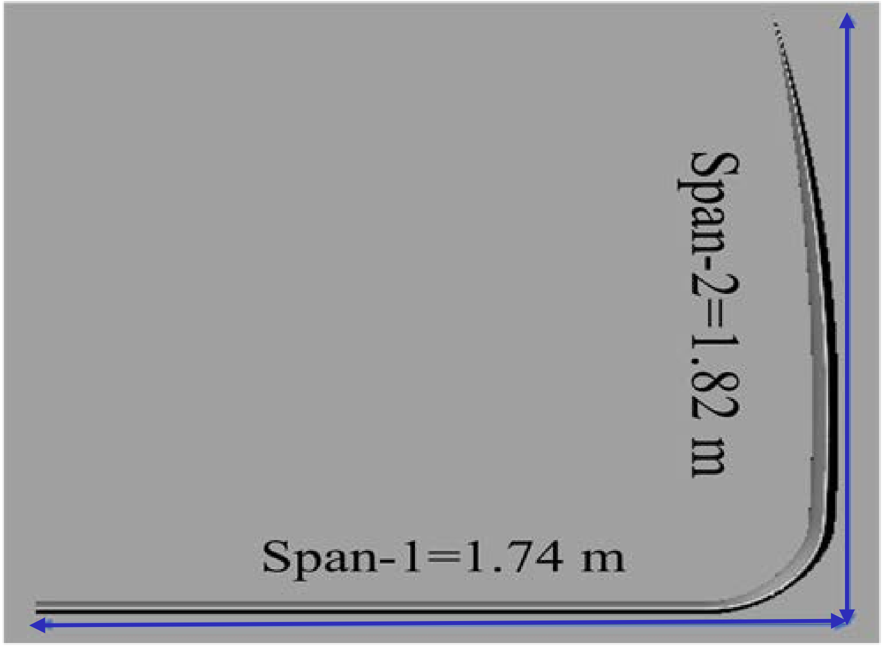
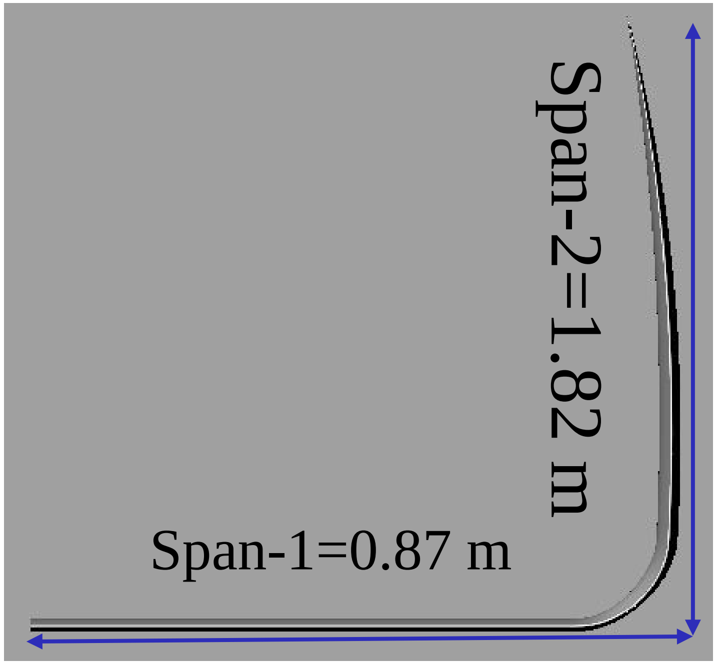

DWL
BL

1/2 & Full Curved Daggerboard Configurations & 40° Canting Keel

Full Size - Effective Draft Values at 15° Heel Angle	
Froude Number - (5.13 m/s)	0,4
1/2 - Curved Foil & 40° Canting Keel	1,10
Full – Curved Foil & 40° Canting Keel	1,04
Only 40° Canting Keel	0,95

Full Size - Heave Analysis Values of 1/2 -Full Curved Foils	
15° Heel Angle & 0.40 Froude Number (5.13 m/s)	
Better Configuration – Full - Curved Foil	
Lift Force Difference (kN)	4,23
Displacement Difference (tonnes)	0,43





Overall Analyses For Each Foil Configurations in the Upwind Condition

Full Size - Effective Draft Results of 1/2 & Full – Straight & Curved Foils

Sailing Conditions (15° Heel Angle)	Froude Numbers	
	0,3 - (4 m/s)	0,4 (5.13 m/s)
Full - Straight Foil & 40° Canting Keel (m)	1,36	1,15
1/2 - Curved Foil & 40° Canting Keel (m)	1,24	1,10
Full – Curved Foil & 40° Canting Keel (m)	1,14	1,04
Only 40° Canting Keel (m)	1,23	0,95
1/2 – Straight Foil & 40° Canting Keel (m)	1,07	0,92

Full Size - Heave Analysis Values of Full Straight & Full Curved Foils

15° Heel Angle & 0.3 Froude Number (8 knots)

Better Configuration – Full - Curved Foil

Lift Difference (mm)	10,47
Water Plane Area- 15° Heel (m²)	39,77
Lift Force Difference (kN)	4,19
Displacement Difference (tonnes)	0,43

Full Size - Heave Analysis Values of Full Straight & Full Curved Foils

15° Heel Angle & 0.4 Froude Number (10 knots)

Better Configuration – Full - Curved Foil

Lift Difference (mm)	11,07
Water Plane Area- 15° Heel (m²)	39,77
Lift Force Difference (kN)	4,43
Displacement Difference (tonnes)	0,45

Final Ranking List of Vendée Globe 2016-2017

AT 22H00	SKIPPER/BOAT	PROGRESS	DISTANCE TO FINISH	HEADING	SPEED VMG
1	Armel LE CLÉAC'H BANQUE POPULAIRE VIII			Arrived on 19/01/17 at 16:37 Race time : 74d 03h 35m 46s	
2	Alex THOMSON HUGO BOSS			Arrived on 20/01/17 at 08:37 Race time : 74d 19h 35m 15s (+15h 59m 29s)	
3	Jérémie BEYOU MAITRE COQ			Arrived on 23/01/17 at 19:40 Race time : 78d 06h 38m 40s (+4d 03h 02m 54s)	
4	Jean-Pierre DICK StMICHEL-VIRBAC			Arrived on 25/01/17 at 14:47 Race time : 80d 01h 45m 45s (+5d 22h 09m 59s)	
5	Yann ELIES QUÉGUINER - LEUCÉM...			Arrived on 25/01/17 at 16:13 Race time : 80d 03h 11m 09s (+5d 23h 35m 23s)	
6	Jean LE CAM FINISTÈRE MER VENT			Arrived on 25/01/17 at 17:43 Race time : 80d 04h 41m 54s (+6d 01h 06m 08s)	

Boat with hydrofoils

The Record Race Time was 78 days

CONCLUSIONS

- **Despite being less efficient, the 40° canting keel has more righting arm (GZ) advantage due to the bulb weight as compared with 0° canting keel.**

- **In general, the additional daggerboards improve efficiency of side force generation of the sailboat in the upwind condition.**

- **The Full – Straight Foil is the most efficient configuration as compared with others in the upwind conditions.**

- **The Full - Size foil configurations generate more lift force than the 1/2 daggerboard shapes due to longer span length.**

- **The Curved Foil Configurations have more lifting advantage as compared with Straight Foils based on the lift analyses. The lifting advantage is a critical ability for the boat speed despite being less efficient in upwind conditions after all.**

Recommendations & Future Works

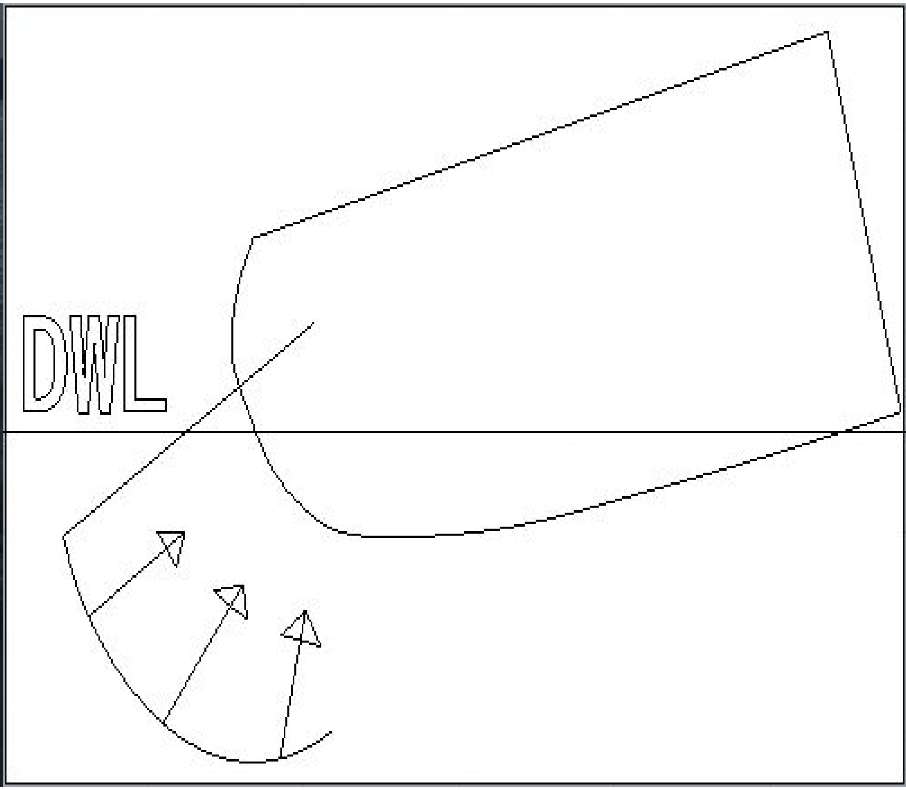
- **The angle of attack (1.5°) was not great enough to generate side force for curved foils so the toe angle should be increased in next experimental tests.**

- **The all towing tank tests can be performed in CFD in order to compare the drag and lift results.**

- **Different foil designs can be tested in either CFD or towing tank tests to find better foil shape in upwind and downwind conditions.**

The Foil Configuration of the Le Figaro Bénéteau 3

- **There is a new monohull racing sailboat design which will be launched by Bénéteau.**
- **When the sailboat is heeled, the horizontal side force vector turns into lift force vertically because of shape of the foil and moving inward.**



Thanks For Your Attendance !