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7th EMship cycle: October 2016 – February 2018

Master Thesis

Design of a Cruising Sailing Yacht with an Experimental Fluid Dynamics Investigation into Hydrofoils

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La Spezia, February 2018

1. Aim and Methodology

Part 1: Design

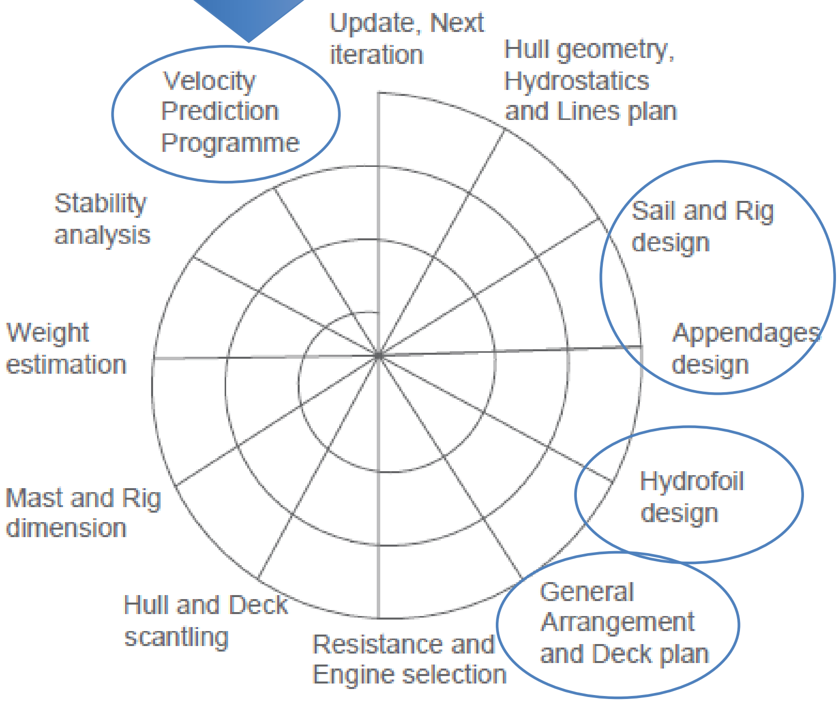
Design of the **Cruising Yacht** and **Hydrofoils** + **VPP** plot

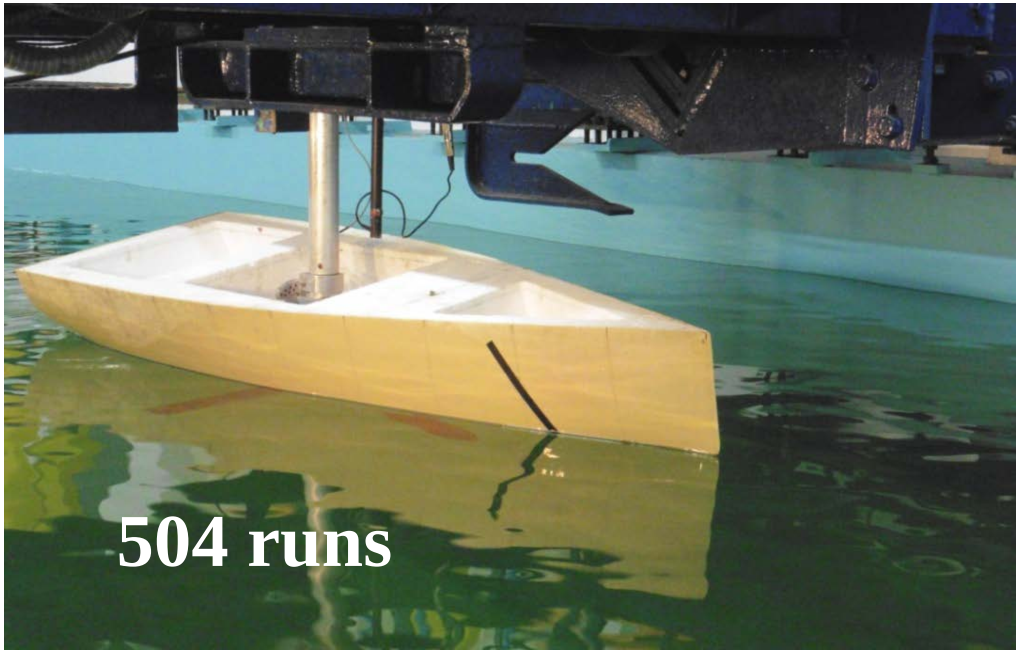
→ **Part 2: Hydrodynamics**

Construction of the model in Southampton Solent University

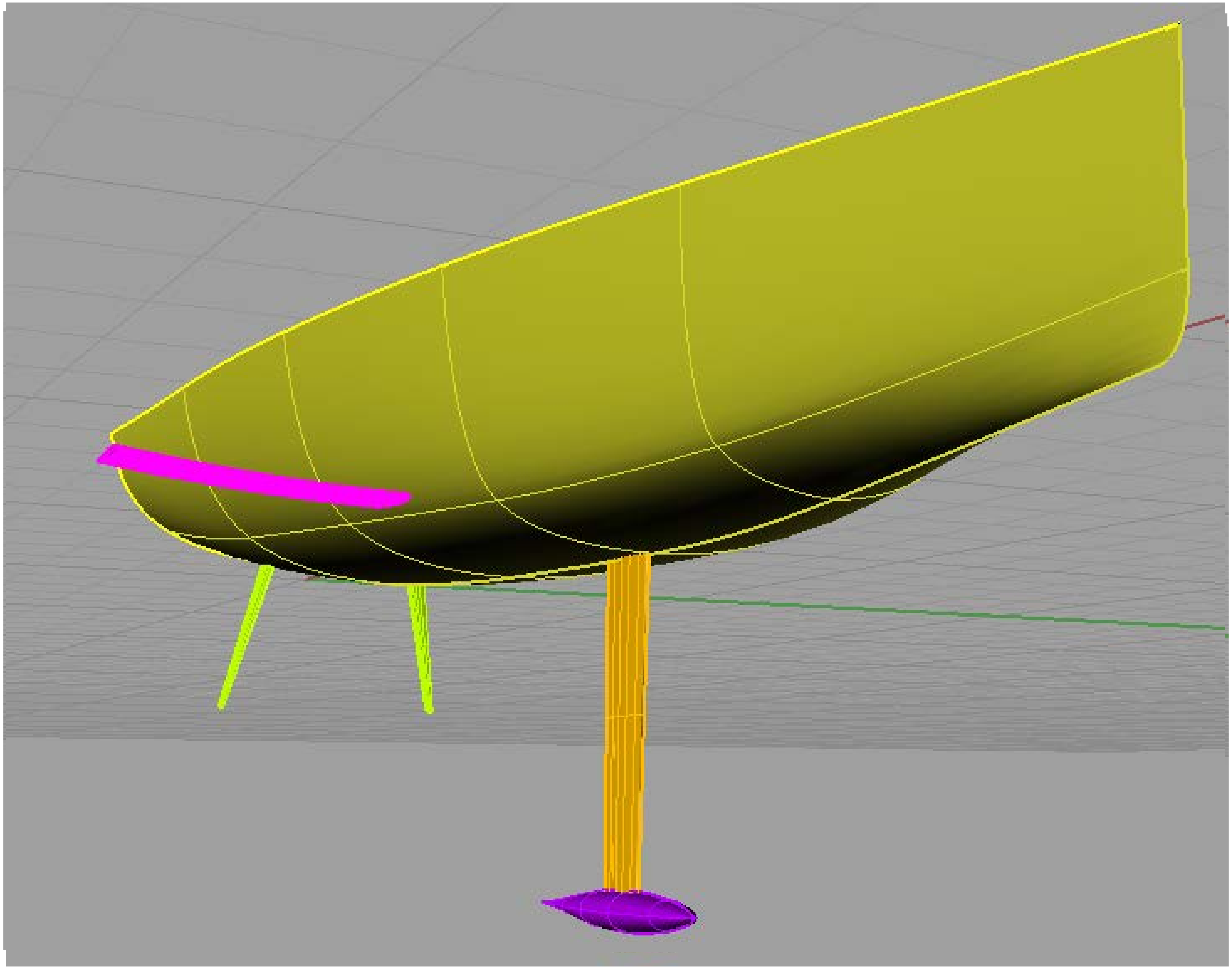
→ **Test in the Towing tank** – ITTC procedures

→ **Hydrodynamic results** analysis:
- Heave
- Trim
- Resistance
- Side force





1 cruising yacht, 3 hydrofoil configurations:



Cruising yacht
50 feet

+

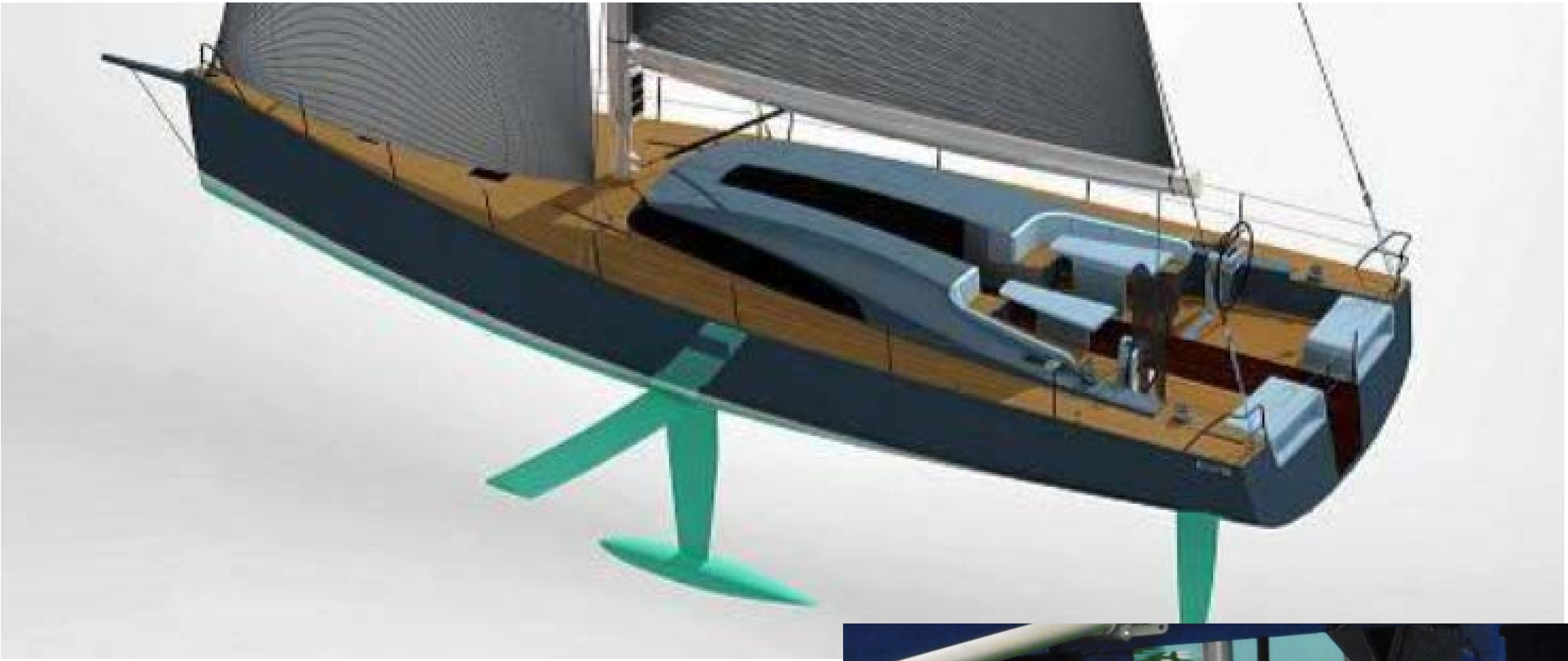
Dali
moustache

Figaro 3

DSS

Chistera foil - Figaro 3
Bénéteau yacht

Dali Moustache – IMOCA 60
Safran II yacht

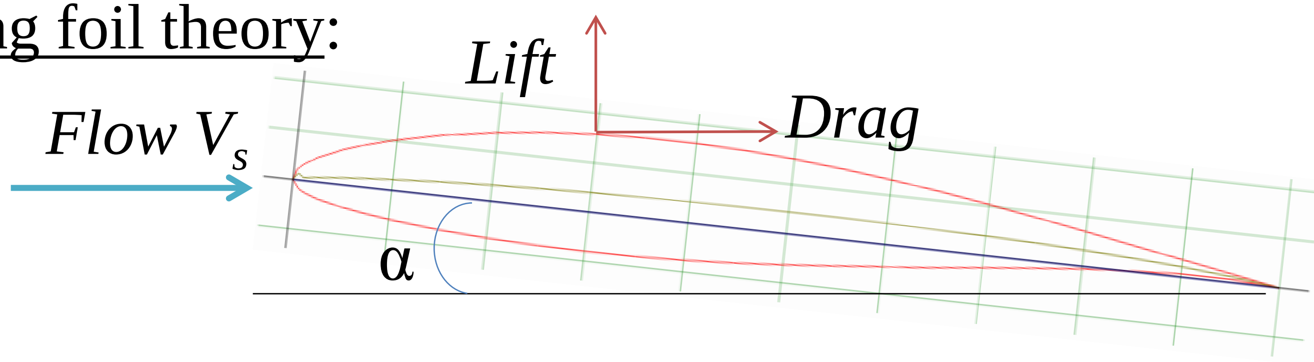


DSS foil –
Infiniti 56 yacht

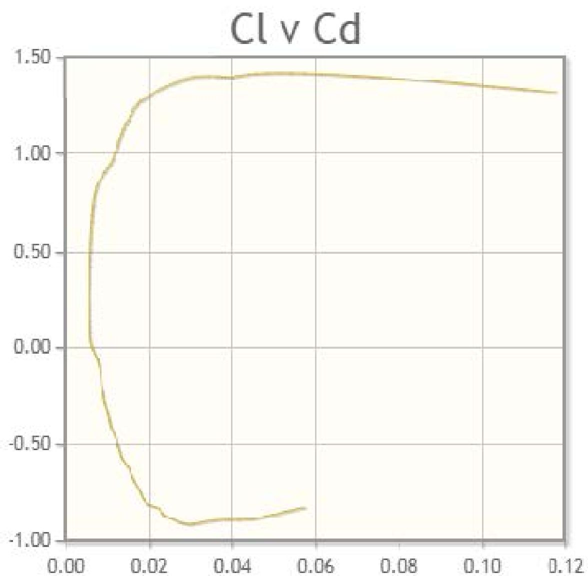
Basic 2D Lift and Drag foil theory:

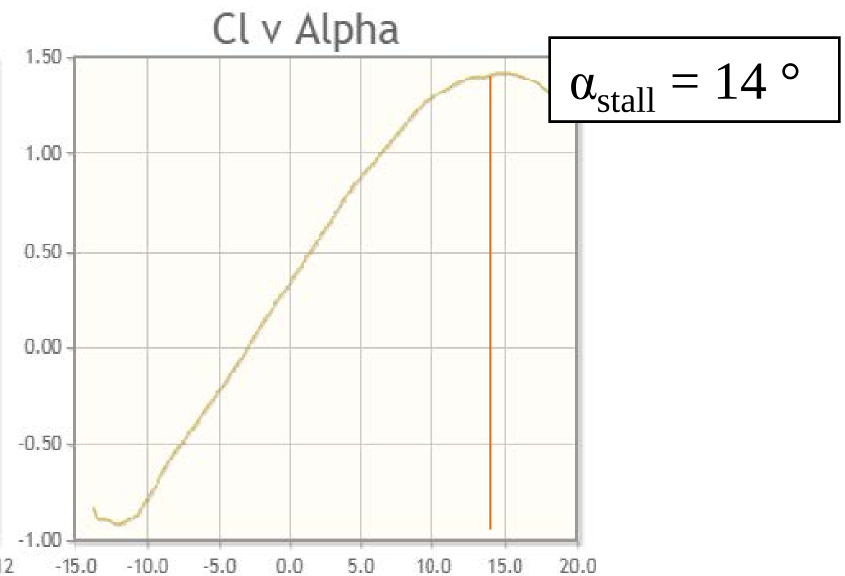
$$L = C_L \,.1/2.\, \rho \; WSA \; V_S^{\,2}$$

$$D = C_D \,.1/2.\, \rho \; WSA \; V_S^{\,2}$$



Same section for the three hydrofoils: **NACA 63-412**

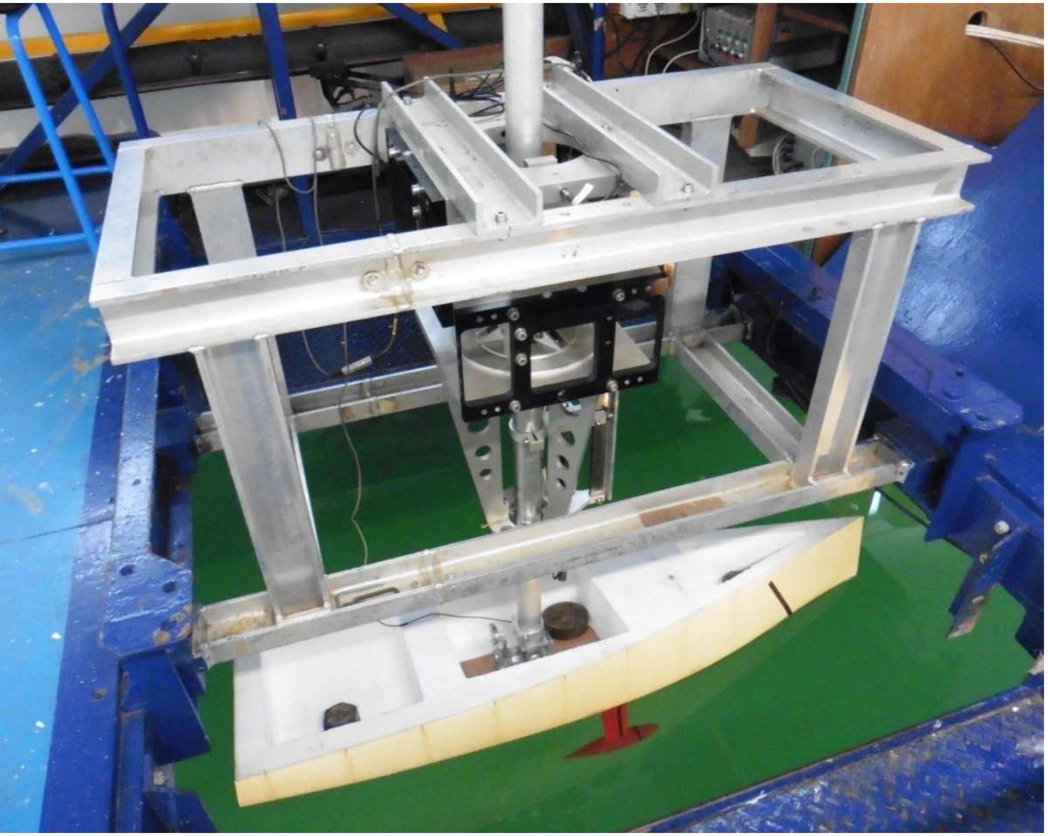


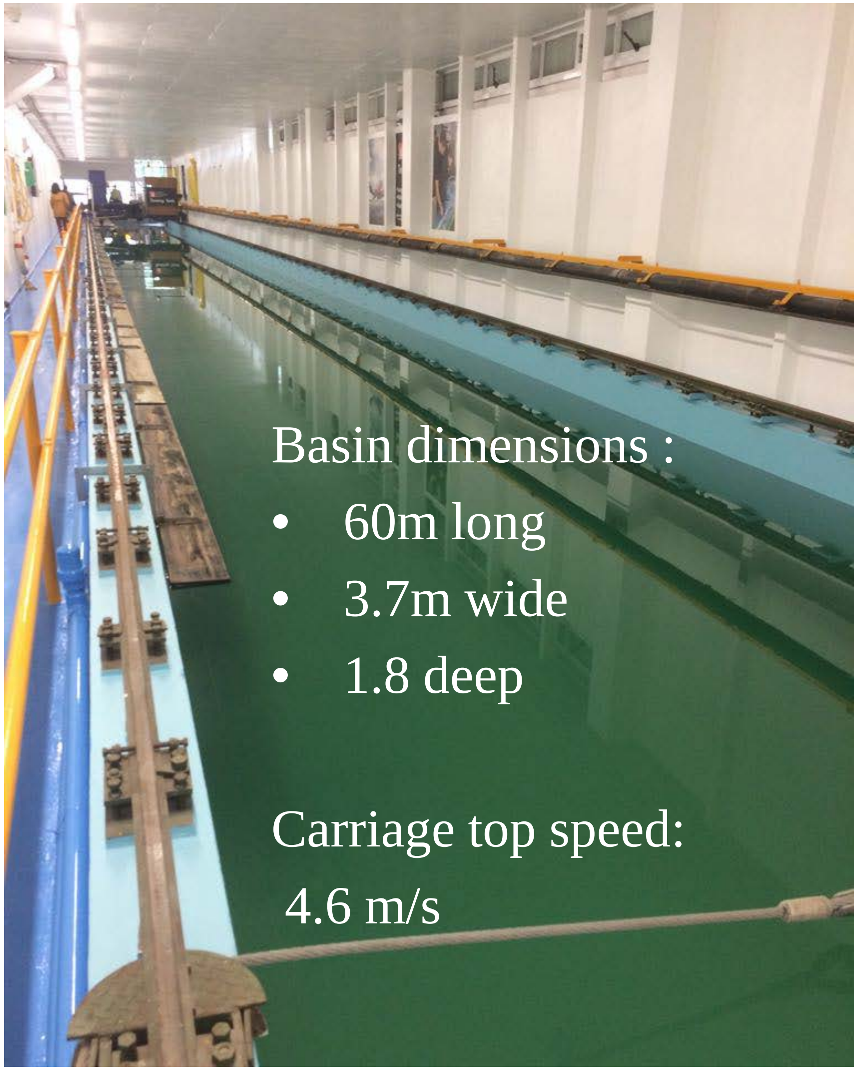


Lift and Drag coefficient for Re = (Vs.c)/v = 5.E+06

3. Towing Tank facility in Southampton Solent University

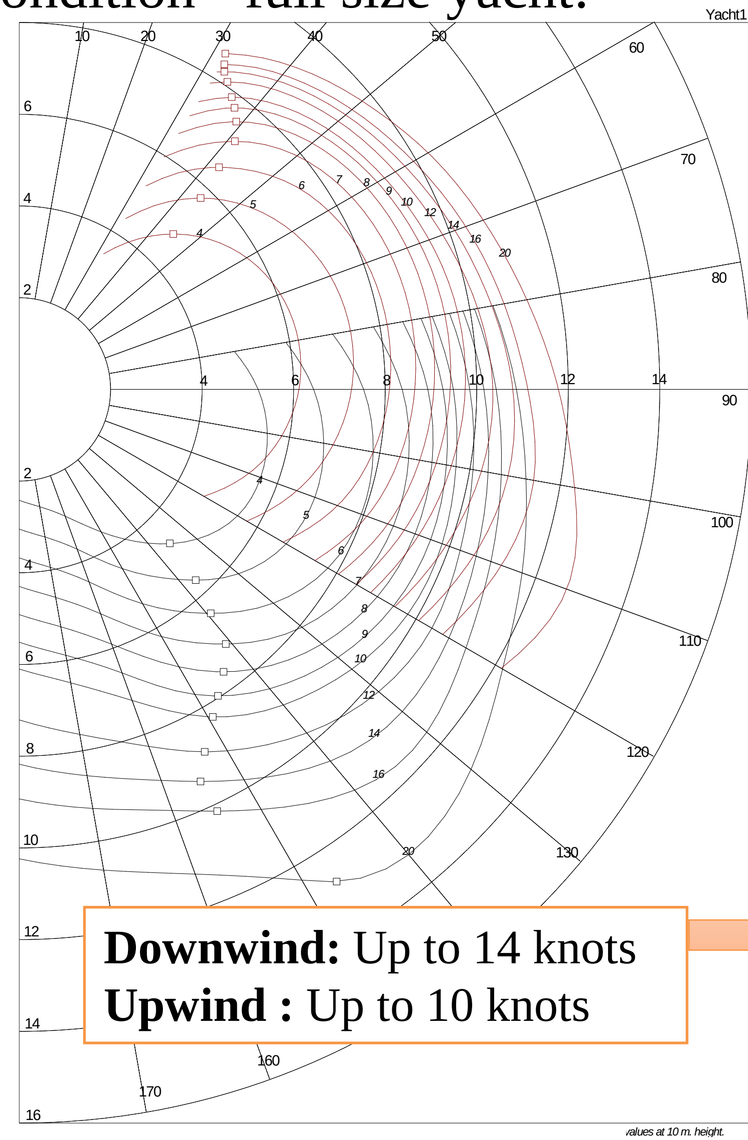
1.50 m model
Scale 1:10





<u>ITTC Procedures:</u> <u>Workshop</u> => ITTC procedures for ***Ship model***
<u>Towing tank</u> => ITTC procedures for ***Resistance Tests***

VPP plot in **upwind** and **downwind** condition - full size yacht:



Downwind: Up to 14 knots
Upwind : Up to 10 knots

Measurements in the towing tank – **Hydrodynamic results model size**:

Control:
- Velocities (m/s) or Froude number
- Heel angles (°)
- Yaw or Leeway angles (°)
- Foil angle of attack (***fixed***)

Measurement:
- HEAVE (mm)
- TRIM (°)
- DRAG (N)
- SIDE FORCE (N)

	Upwind	Downwind
Speed	Fr 0.35 to 0.45	Fr 0.45 to 0.70
Heel	θ = 20°	θ = 10°
Yaw	Leeway = 4/6°	Leeway = 0/2°

Froude Similarities & ITTC 57 guidelines:

- ***Froude similarities*** implies that the **Froude number** and the **wave resistance** coefficient are equal:

$$Fr_{model} = Fr_{ship}, \text{ and } C_{W,model} = C_{W,ship}$$

- $V_{model} / \sqrt{(g.L_{model})} = V_{ship} / \sqrt{(g.L_{ship})}$

$$\Rightarrow V_{ship} = V_{model} . \sqrt{\lambda}$$

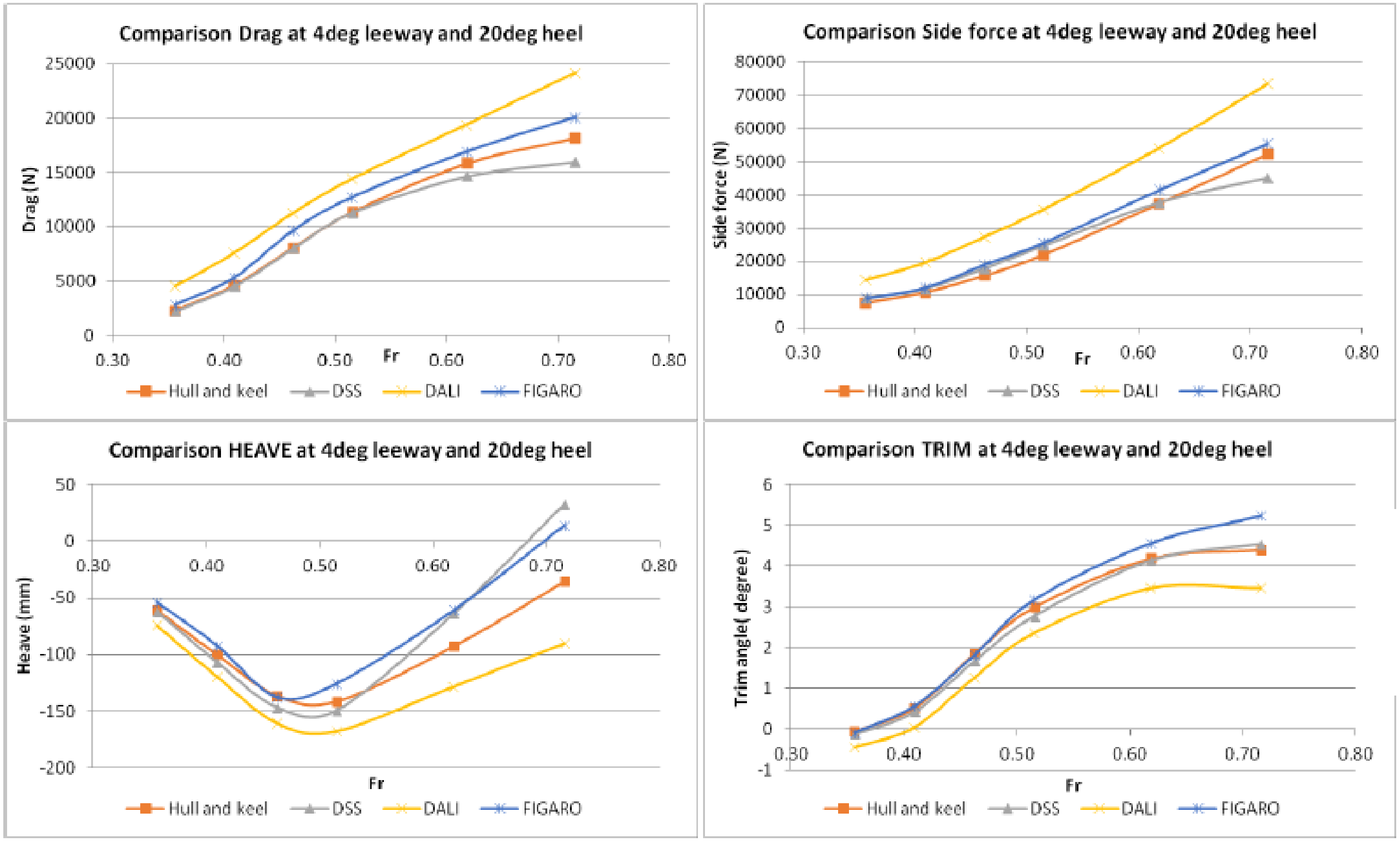
Hydrodynamic results **Model scale** → **Scale factor $\lambda = L_s/L_m = 10$** → Hydrodynamic results **Full scale**

- $C_T (Re, Fr) = (1+k)\, Cf (Re) + Cw(Fr)$

Prohaska's method – Form factors

$$C_T/Cf = (1+k) + a.(Fr^4/Cf)$$

Heave, Trim, Drag and Side force:



Example of graph for upwind condition at high heel angle

Foil	WSA at 20° heel
Dali	3.71 m^2
Figaro	1.73 m^2
DSS	2.04 m^2

$$L = C_L\, .1/2.\, \rho\, WSA\, V_S^{\,2}$$

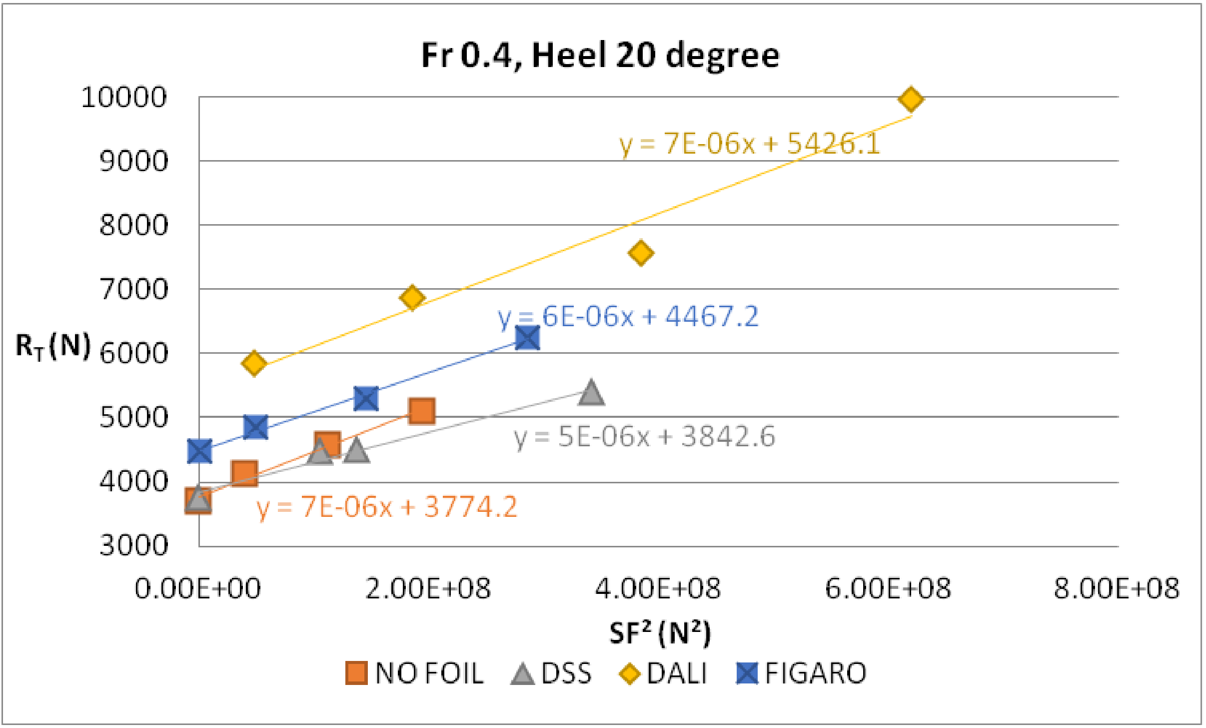
$$D = C_D\, .1/2.\, \rho\, WSA\, V_S^{\,2}$$

1st conclusion: Foils are **useless in term of pure hydrodynamics**!
The benefit is most likely in **STABILITY** (increased RM) or **SEAKEEPING**

Effective Draft Method (1):

Best foil in term of the **lowest** **resistance** or induced drag :

Total drag R_T vs side force squared SF^2 at various leeway angles for a given heel angle and velocity.



Example of graph for upwind condition at low Froude number and high heel angle

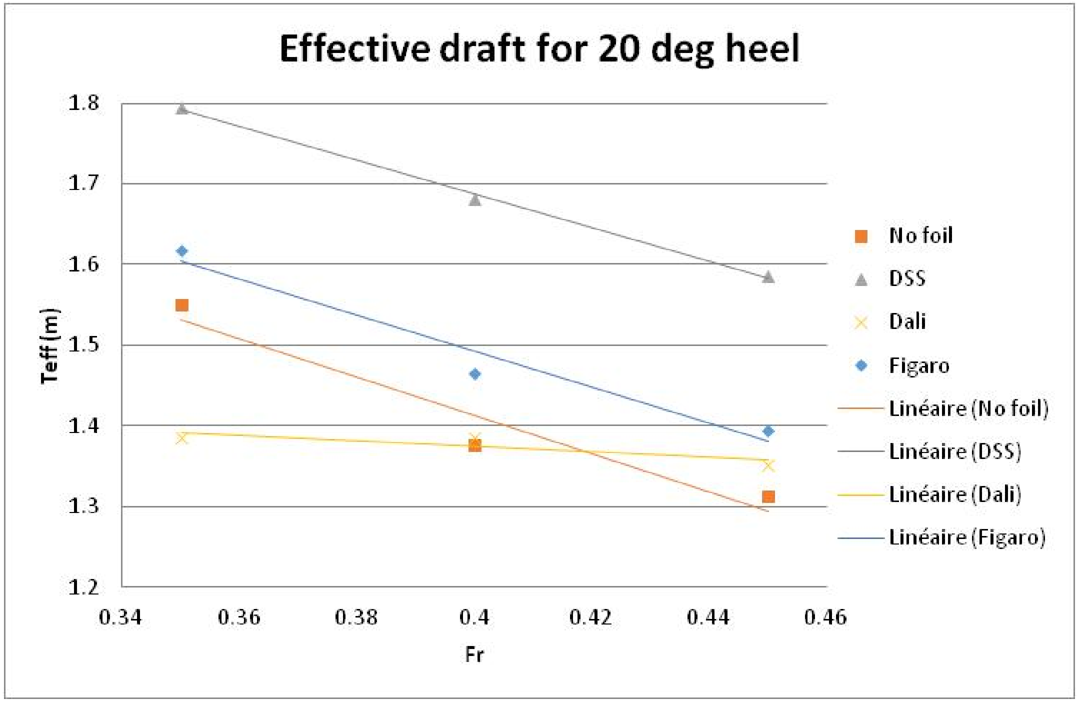
Best configuration selected based on the lowest slope: $y/x = R_T / SF^2$

Rt vs SF²	Heel	10 degree	20 degree
	Leeway	0/2°	4/6°
Fr			
0.35		Keel	**DSS**
0.4		DSS	**DSS**
0.45		**Keel**	**DSS**
0.5		**Dali**	DSS
0.6		**DSS**	DSS
0.7		**DSS**	Keel/DSS

Effective Draft Method (2):

Best foil in term of **generating lift**:

Effective Draft T_E vs Froude number Fr



Example of graph for upwind condition for high heel angle

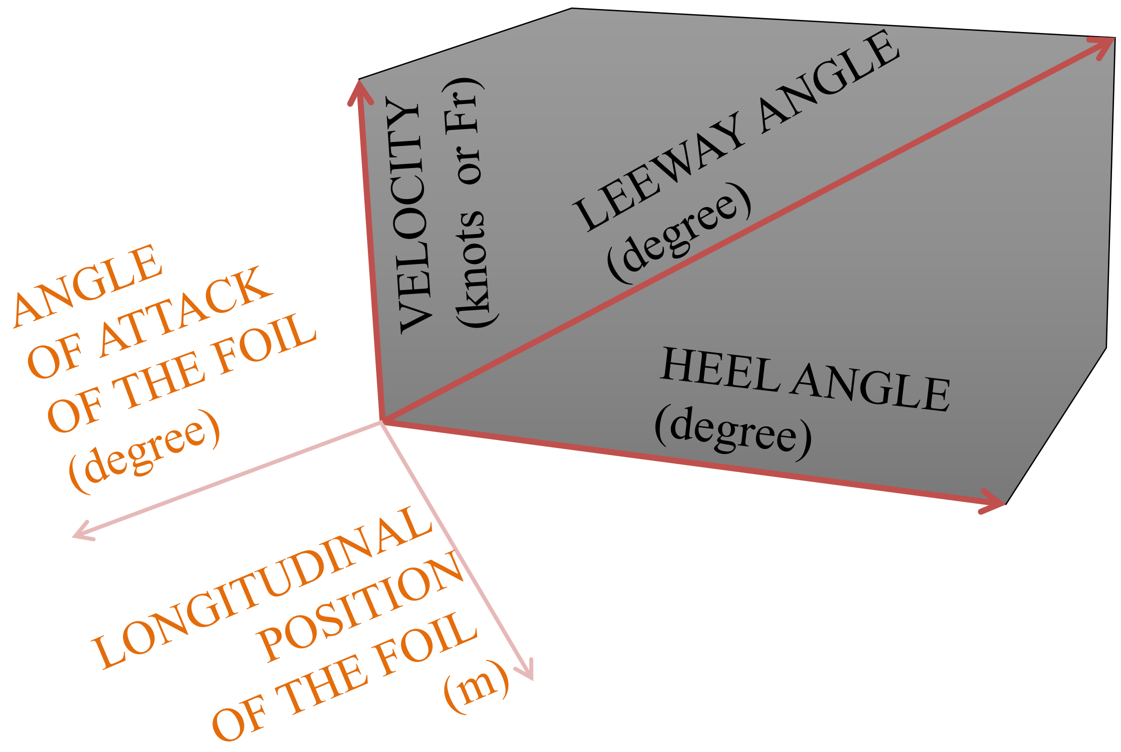
Best configuration selected based on the highest value of the effective draft

$T_E = \sqrt{(0.9.SF^2 /(R_T.\ \pi\ \rho.V_S^2))}$

T_E vs Fr	Heel	10 degree	20 degree
	Leeway	0/2/4/6°	0/2/4/6°
Fr			
0.35		DSS	DSS
0.4		DSS	DSS
0.45		DSS	DSS
0.5		DSS	DSS
0.6		Figaro	DSS
0.7		Keel or Dali	Dali

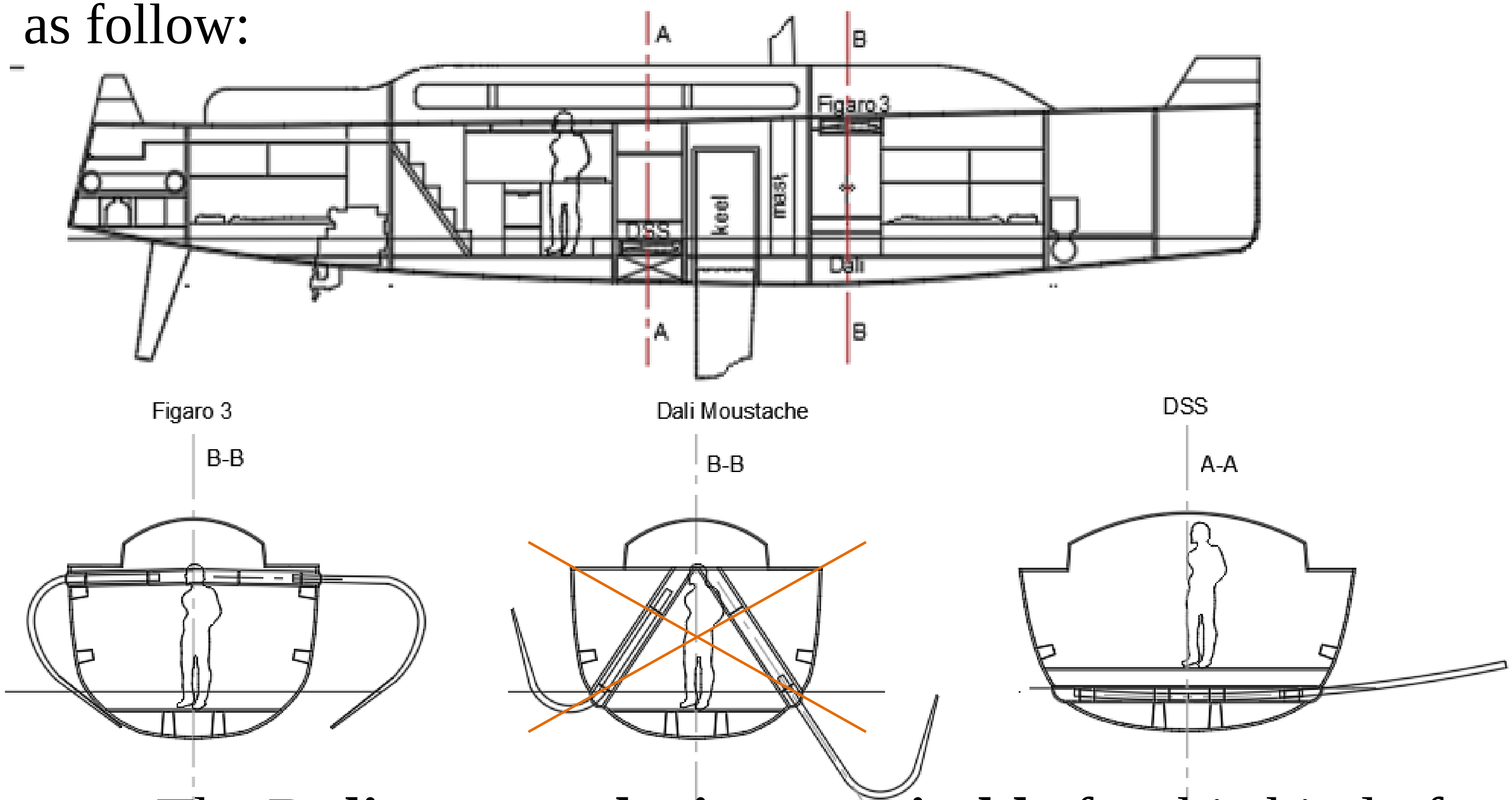
In term of **MINIMUM DRAG**, the **DSS is the most efficient** configuration on this model, both for upwind and downwind conditions

We have seen previously that the velocity, leeway and heel angle are influencing the hydrodynamic behaviour of the foiling yacht:



Longitudinal position of the foils : **Design** issue

On a design point of view, the foils are integrated in the GA as follow:



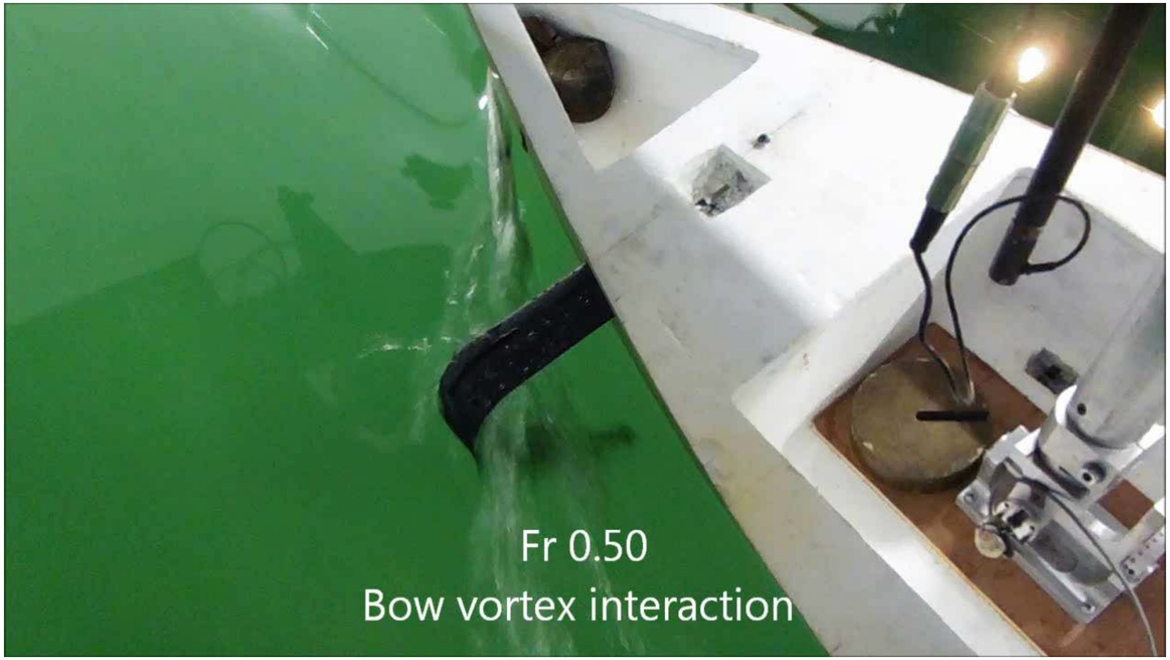
The **Dali moustache is not suitable** for this kind of **cruising yacht** at this longitudinal position

Longitudinal position of the foils : **Hydrodynamic** issue

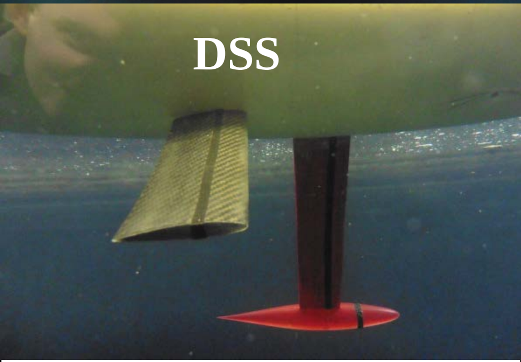
Figaro 3 and Bow vortex interaction:

Bow vortex at higher speeds:

- **Interaction** of the vortex with the foil: i.e. Higher resistance
- **Suction** on the surface of the foil and **sprays** for the highest speeds (0.6 and 0.7): i.e. less WSA but no less drag



→ We can consider other longitudinal position for the foil in order **to avoid the bow vortex**

	ADVANTAGES	DRAWBACKS
	❖ Great **side force** generation ❖ Reduction of the **trim angle**	❖ Huge increase in **resistance** ❖ Needs a **great angle of attack** to get sufficient SF generation ❖Integration in the design: **lack of volume** in the interior layout
	❖ **Good compromise** in between the three foils in terms of small drag and sufficient side force generation ❖ Minor problems for the integration in the interior design	❖ **Longitudinal position** critical due to the bow vortex interaction ❖ Small increase of the **trim angle** in high speeds
	❖ Easy integration in the **design** ❖ Generates **the more lift** ❖ **Minimum drag** configuration for most of the point of sail	❖ Almost no contribution in **side force** ❖ Dependant to a small angle of attack because of the **stall angle**

<u>Design changes on IMOCA new generation:</u>

No need to make the hull more efficient, we are looking for **less resistance**.

The yacht can have a **reduced beam** since the foil increases the stability.

➔less **WSA**

➔less **Drag**

➔and **Lighter**

<u>Vendée Globe 2020</u>

Vue d'architecte du futur bateau Charal. | Jérémie Beyou racing/ Charal

Questions ?