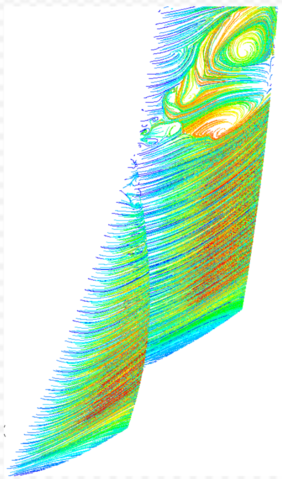
SAILS AERODYNAMICS

A seatrip around sail shapes



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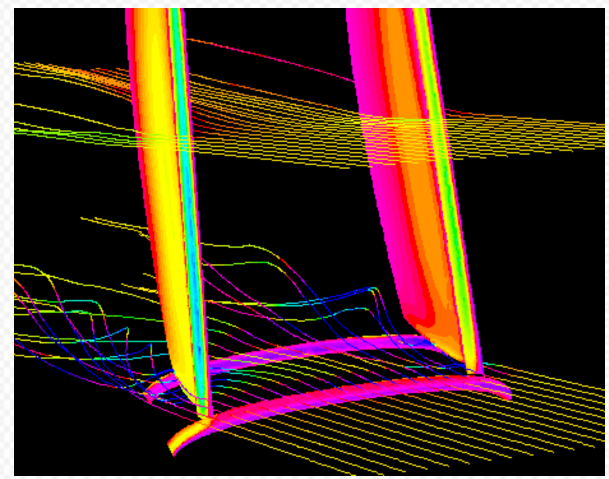
SUPAERO



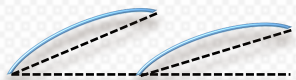
V.G. Chapin,

Marine 2017, Nantes

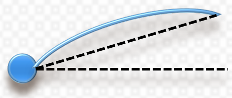
« Ceux qui pensent que c'est impossible sont priés de ne pas déranger ceux qui essaient. »

OUTLINE

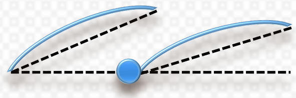
Sail: Curry (1925)



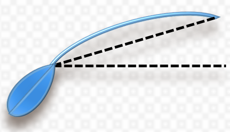
Sails interaction: Gentry, Marchaj,… (1970-80)



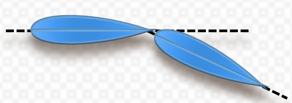
Mast-Mainsail: Wilkinson (1985), Chapin (2005)



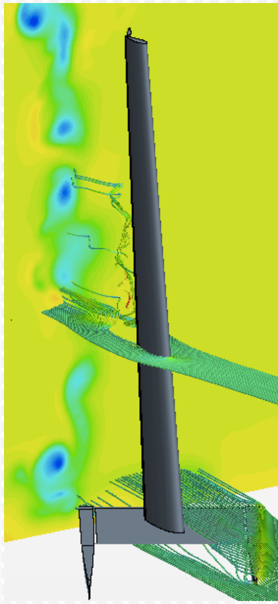
Mast-mainsail-jib: …

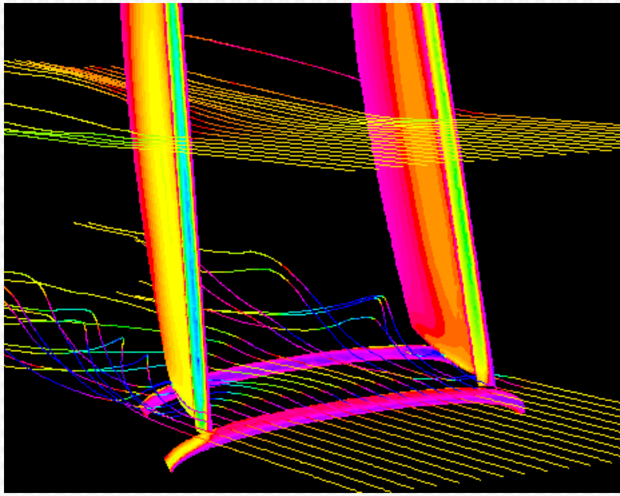


Wingast-mainsail: …



Wingsail: Fiumara (2015)





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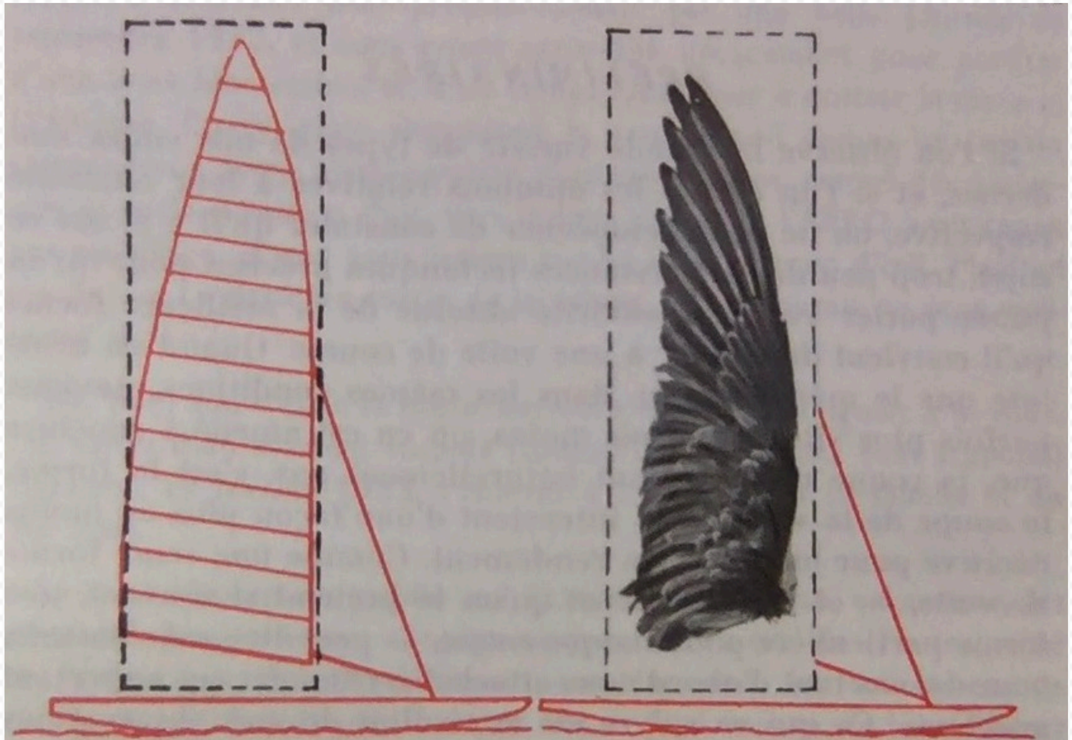
SUPAERO

1925 SAIL SHAPE - M. CURRY



Voile de yacht et aile d'oiseau.

« …Rigs: a large variations of types and shapes... »

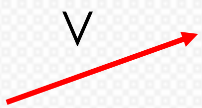
« Sparse scientific knowledge to infer the best sail shape »

« One sail shape is optimum in given wind & sea conditions »

« **Which is the best shape ?** »

M. Curry (1925)

SAILS INTERACTION



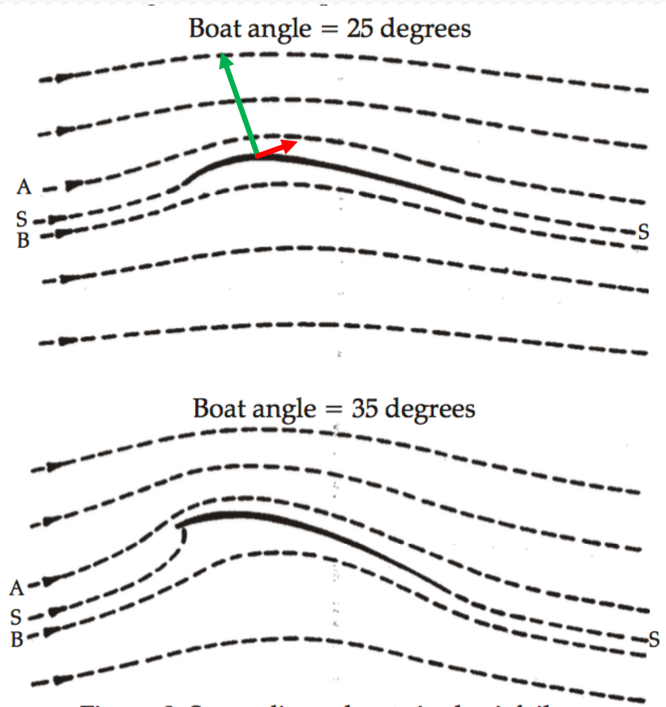
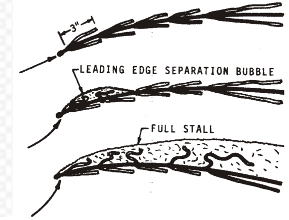


Figure 8. Streamlines about single airfoil.

70-80'S GENTRY SAILS INTERACTION



- **Potential flow** => scientific analysis
  - 1956 Malavard Exp. Rheoelectric
  - 1965 Giesing 2D Potential code

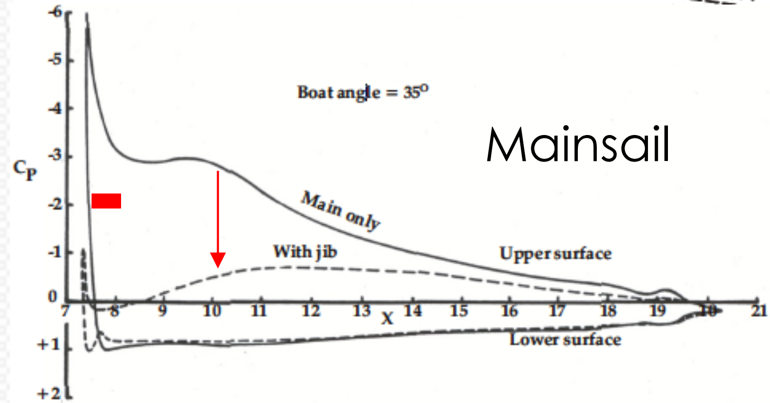
- Subsonic : "All influence all"
  - Adaptation angles mutually changed
  - Mainsail load decreased by jib
  - Jib load increased by mainsail

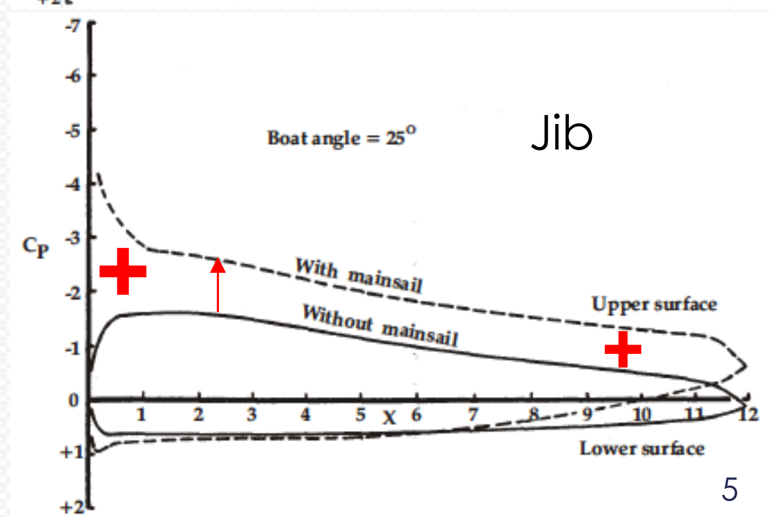
- **Sail design & trim:** a difficult question ?

  - Increase driving force
  - Decrease heeling force

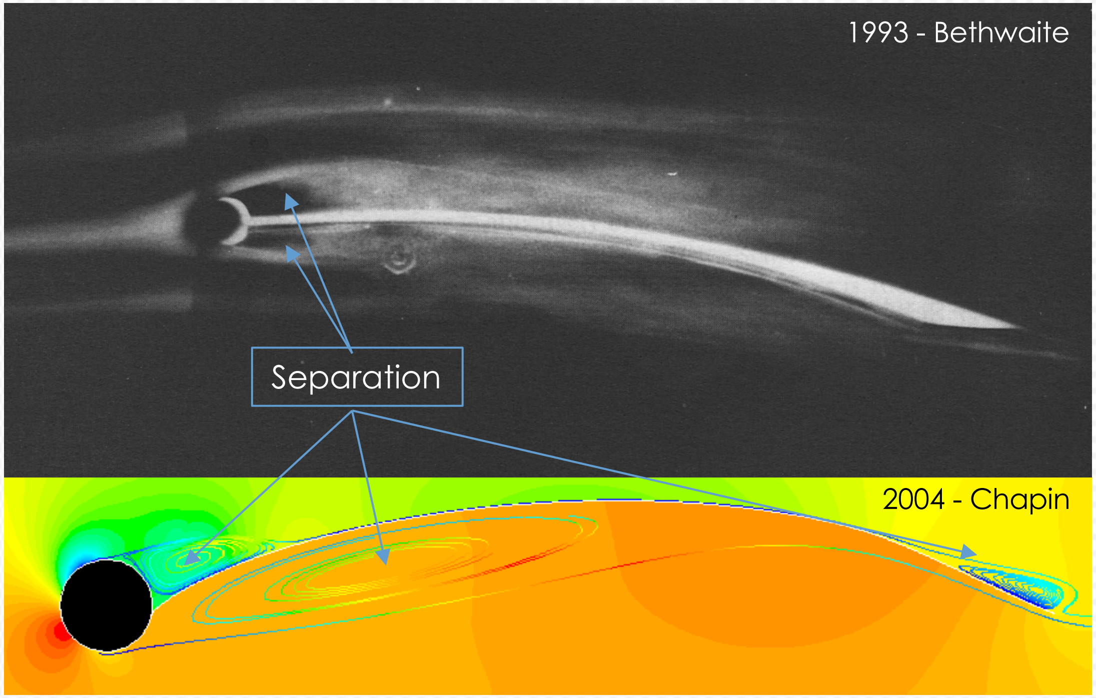
  - Inviscid : Potential flow
  - Viscous : Boundary layer flow
  - Coupling methods

"Understanding sails interaction"



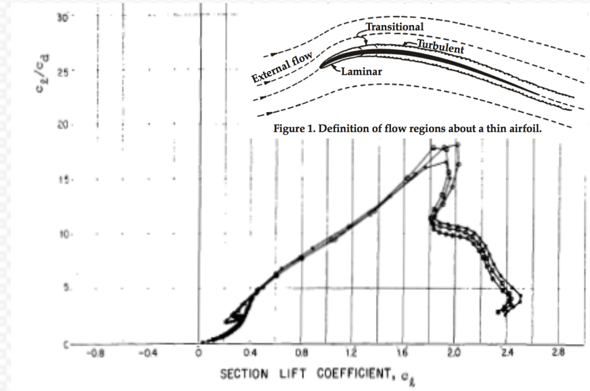


MAST - MAINSAIL



70'S MAST-MAINSAIL

Mast-mainsail = separated flows

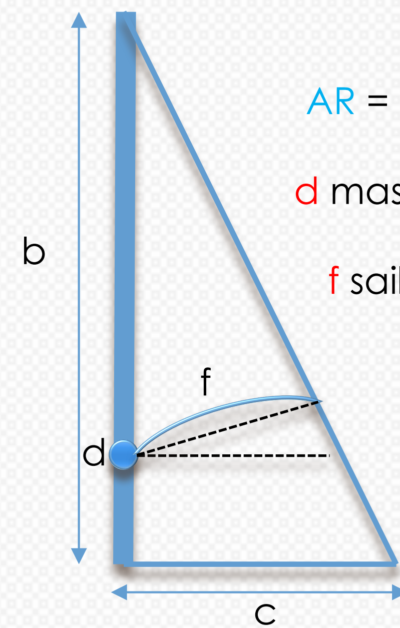


1971 Milgram WT tests on 2D thin sails
f/c=18%, t/c=3.4%, Re=6e5, 9e5, 1.2e6

Controverse Milgram / Marchaj

- 3D inviscid phenomenon AR
- 2D viscous phenomenon d/c

…
1966 Herreshoff WT tests 12-Meter Yacht Mainsail Variations
1968 Milgram "Analytical Design of Yacht Sails" AR, "mast reduce flow separation"
1971 Milgram WT tests on highly cambered 2D thin sails – f/c
1971 Milgram "Sail force coeff. for systematic rig variations" => AR
1976 Marchaj EFD => d/c > AR
1978 Milgram EFD => d/c
1978 Kerwin sail model
1980 Hazen sail model
1989 Wilkinson EFD => d/c, f/c, …
1999 Claugthon sail model
2003 Teeters => masthead effect
2005 Chapin CFD => d/c, f/c effect => mast model …
2006 Fossati EFD => Jib overlap effect in IMS model
…



AR = $b^2/S=2b/c$

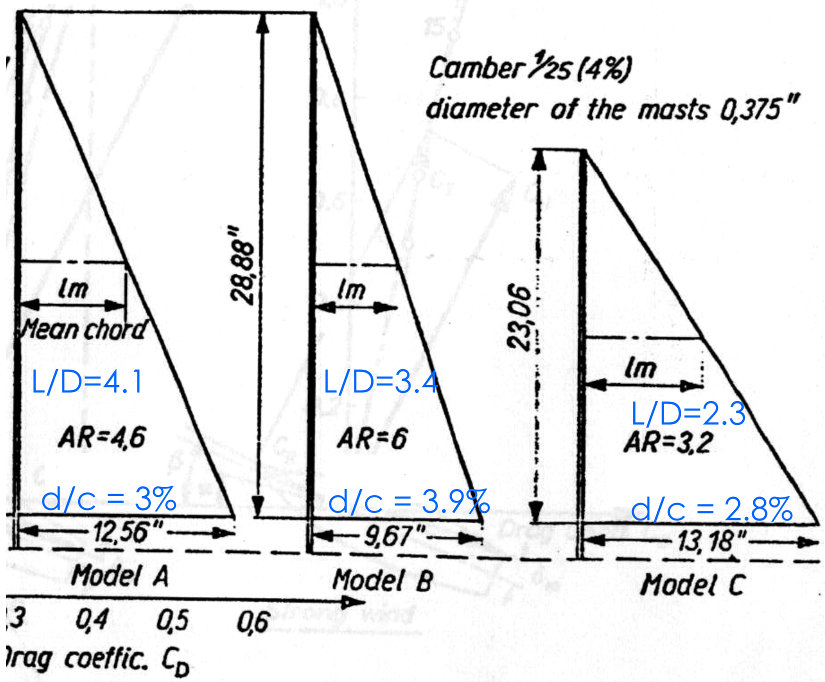
d mast diameter

f sail camber

70'S MAST-MAINSAIL - EFD

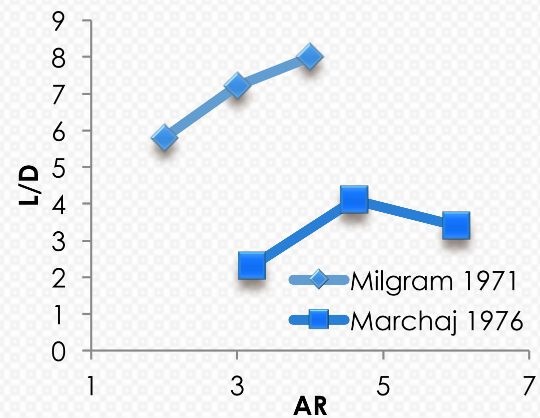
MILGRAM/MARCHAJ

3 sail planform with same mast



Milgram 1971: predict aerodynamic coeff. of thin sails and rigs (**inviscid** VLM method)

Marchaj 1976 : WT tests on a mainsail with a mast



70'S MAST-MAINSAIL - EFD

MILGRAM/MARCHAJ/…

Controverse Milgram / Marchaj

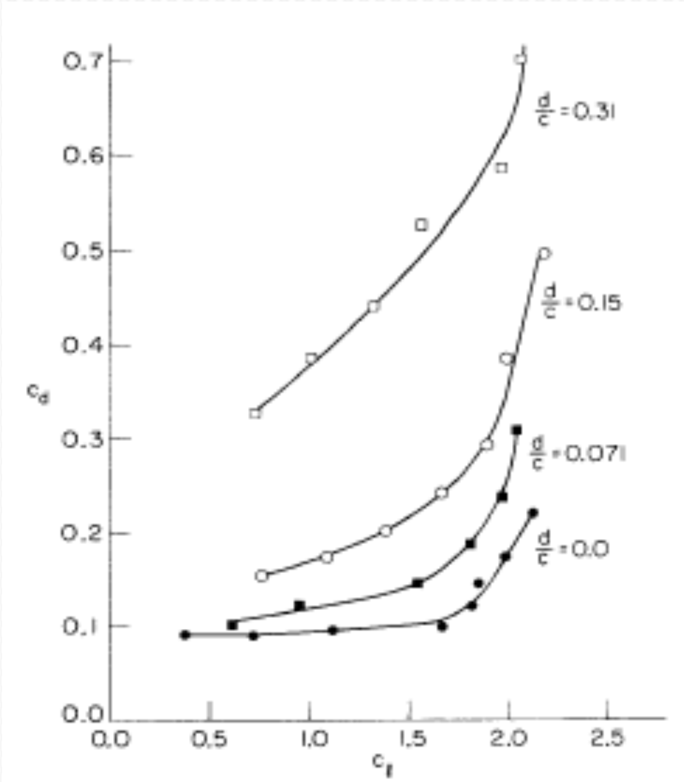
1978 Milgram EFD AR, d/c effects ?

- Mainsail alone $Cd_{2D} = f(f/c, \ldots) \ll Cd_i$
- Mainsail + mast $Cd_{2D} = f(d/c, \ldots) \approx Cd_i$

$$Cd_{mast\text{-}mainsail} \neq Cd_{mast} + Cd_{mainsail}$$

2013 - IMS aerodynamic model

$$C_{dmast\text{-}mainsail} = C_{dmast} + C_{dpv} + C_{dpi}$$



Milgram 1978 WT tests on mast-mainsail configurations

The interaction between a mast and a mainsail is **nonlinear** !

80'S MAST-MAINSAIL – EFD

WILKINSON 1984

a unique experimental work on **mast - mainsail configurations**

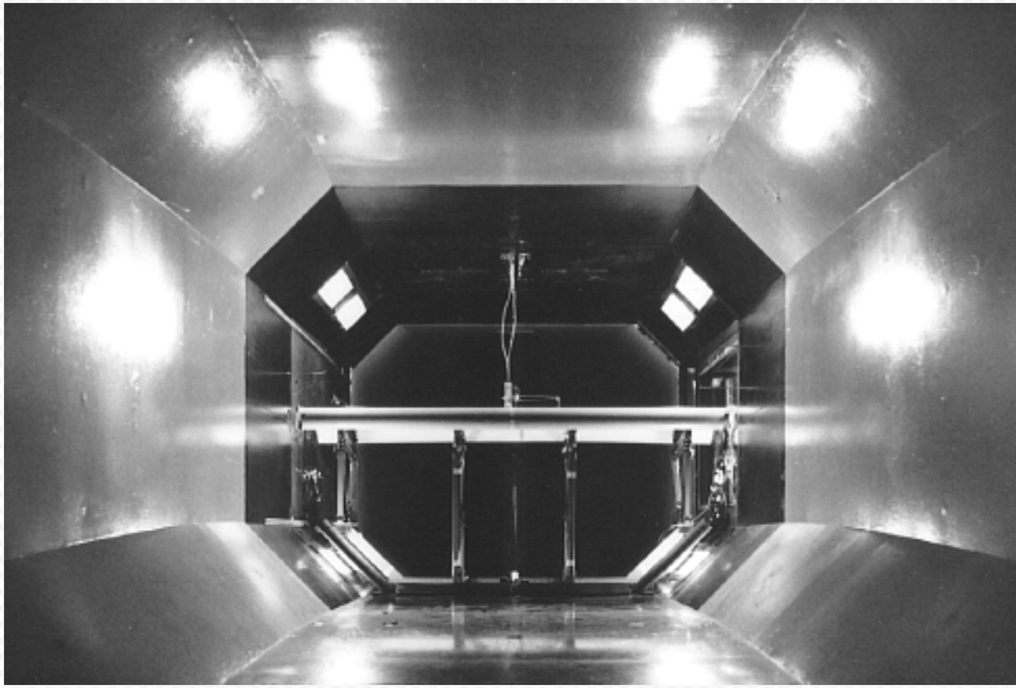
WT tests

Measurements

- Sail surface pressure C_p
- Sail Boundary Layers C_f, X_T, X_R, X_S

Parameters : Aoa, f/c, d/c, Re

192 mast-mainsail configurations !

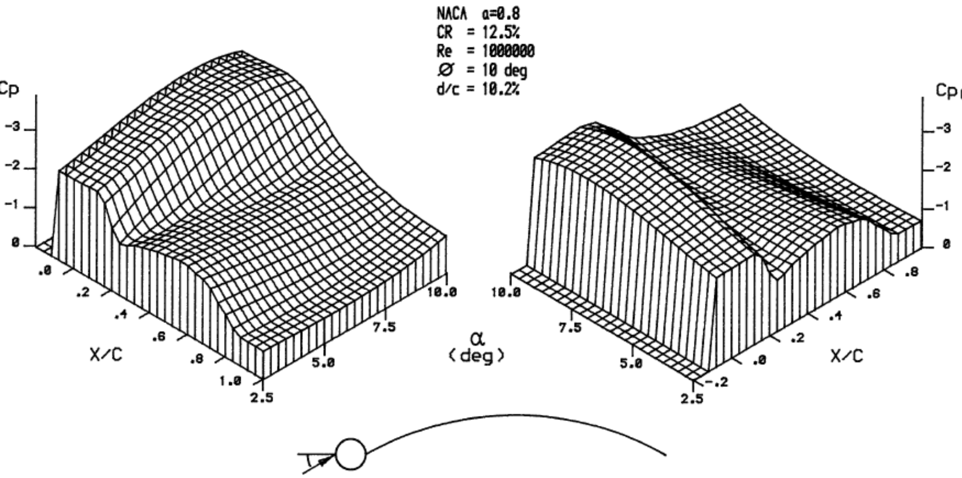


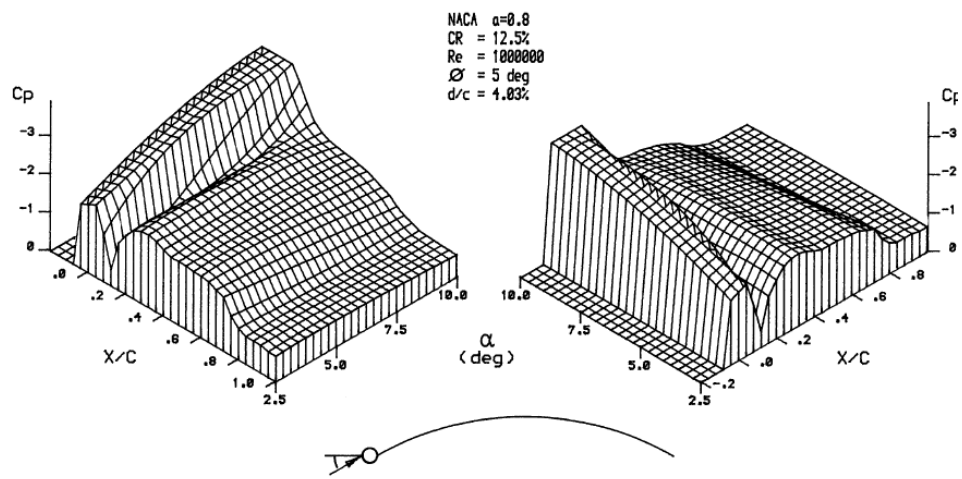
« A huge data base for numerical models validations »

80'S MAST-MAINSAIL – EFD

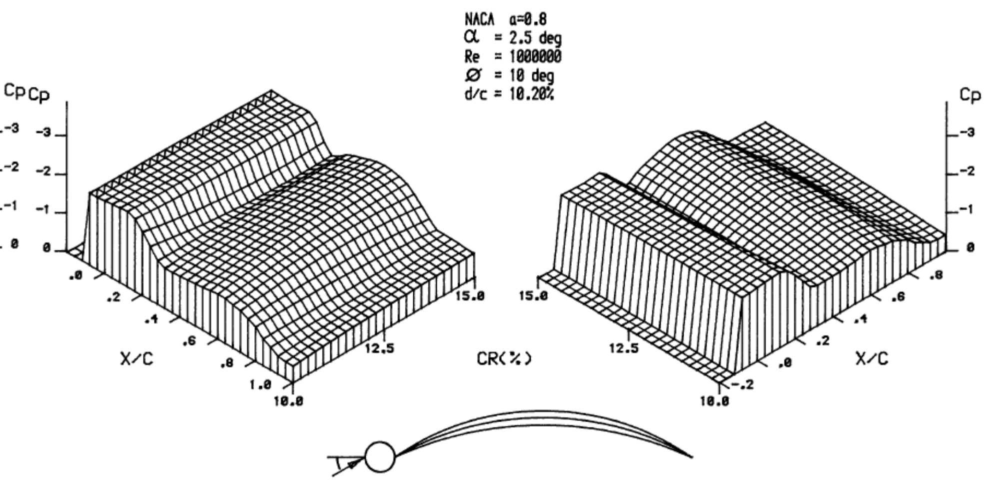
Pressure distribution

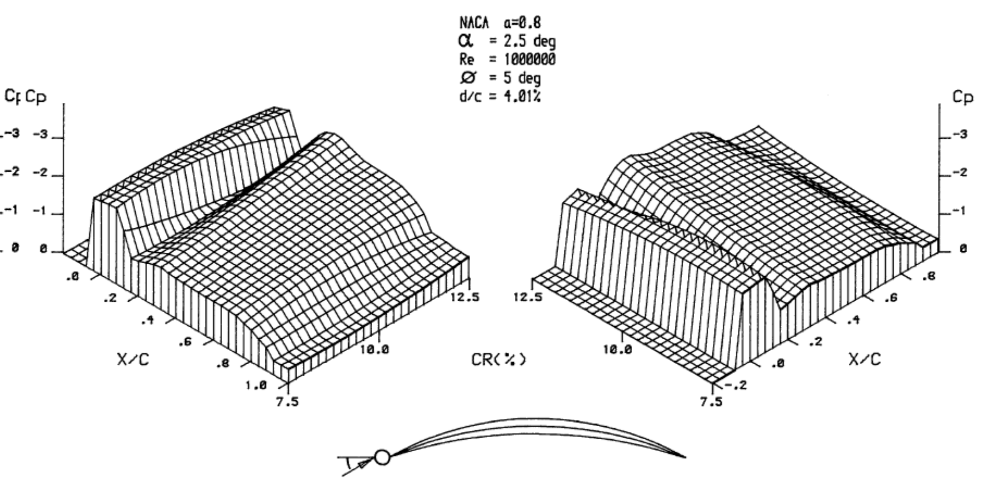
LSB variations with **AoA**
Mast diameter d/c=4%, 10%





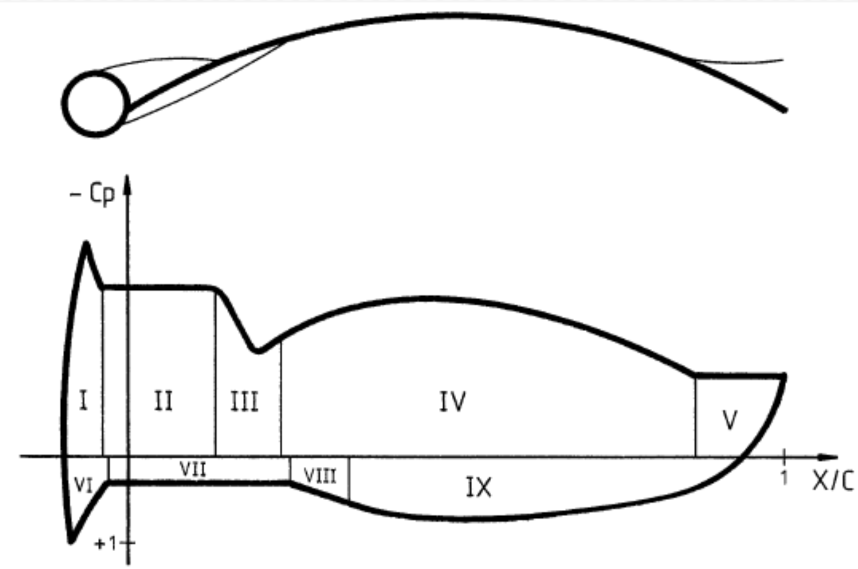
LSB variations with **camber**
Mast diameter d/c=4%, 10%





80'S MAST-MAINSAIL – EFD

Pressure distribution



WILKINSON PHD 1984

A unique database for viscous CFD validations

A UNIVERSAL PRESSURE DISTRIBUTION

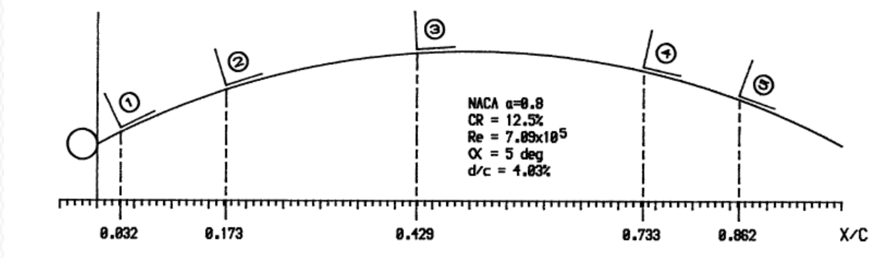
Suction side:
A Laminar separation buble
A transition and reattachment
A Turbulent TE separation

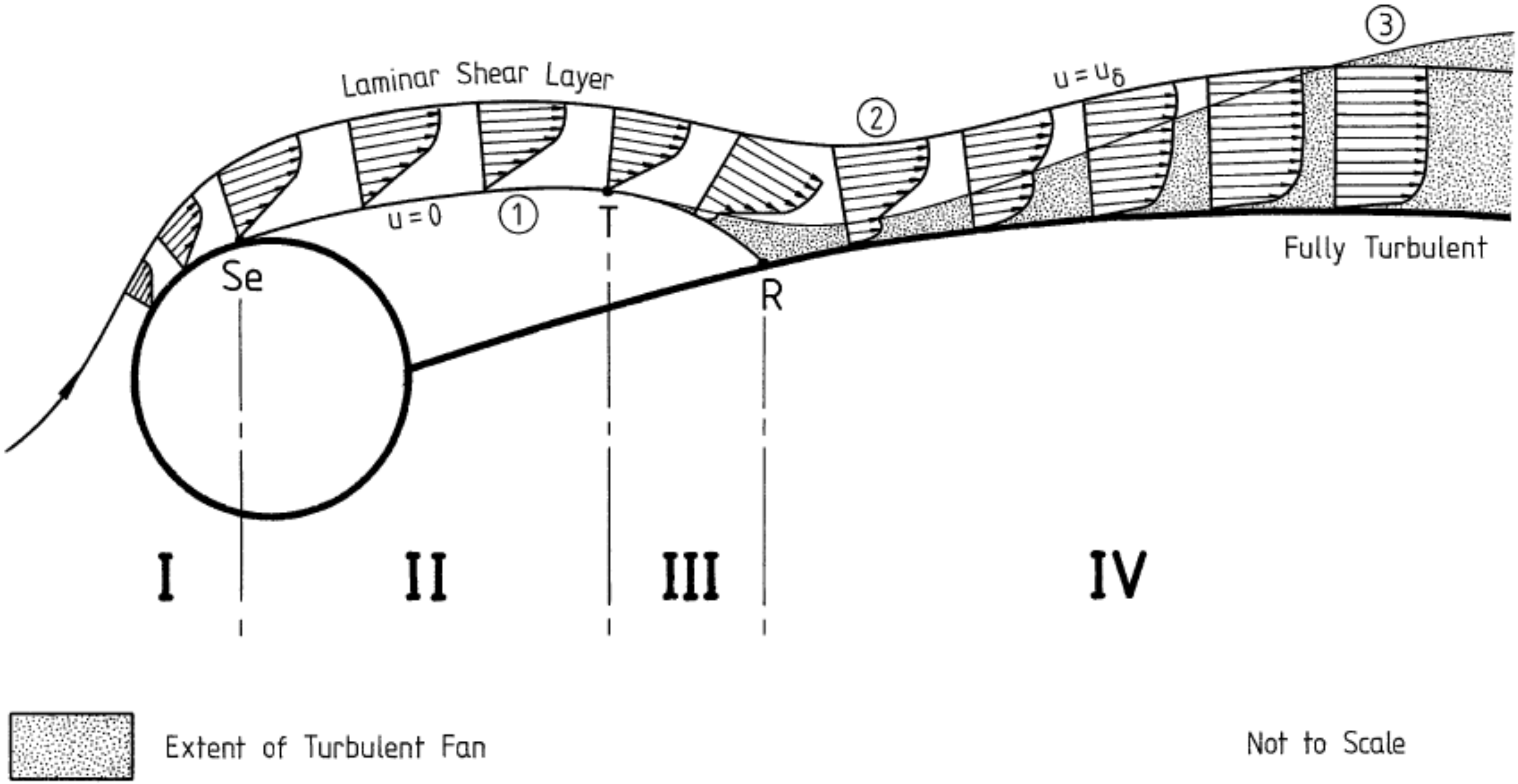
Pressure side:
A Laminar separation buble
A transition and reattachment

REGION	DESCRIPTION	
I	Upper Mast Attached Flow Region	
II	Upper Separation Bubble	X_S
III	Upper Reattachment Region	X_R
IV	Upper Aerofoil Attached Flow Region	
V	Trailing Edge Separation Region	X_S
VI	Lower Mast Attached Flow Region	
VII	Lower Separation Bubble	
VIII	Lower Reattachment Region	
IX	Lower Aerofoil Attached Flow Region	

80's MAST-MAINSAIL – EFD

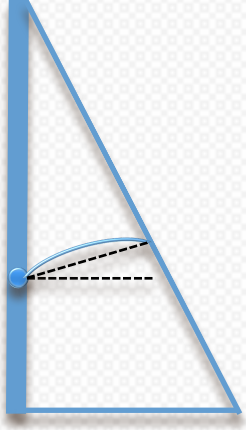
Boundary layer measurements





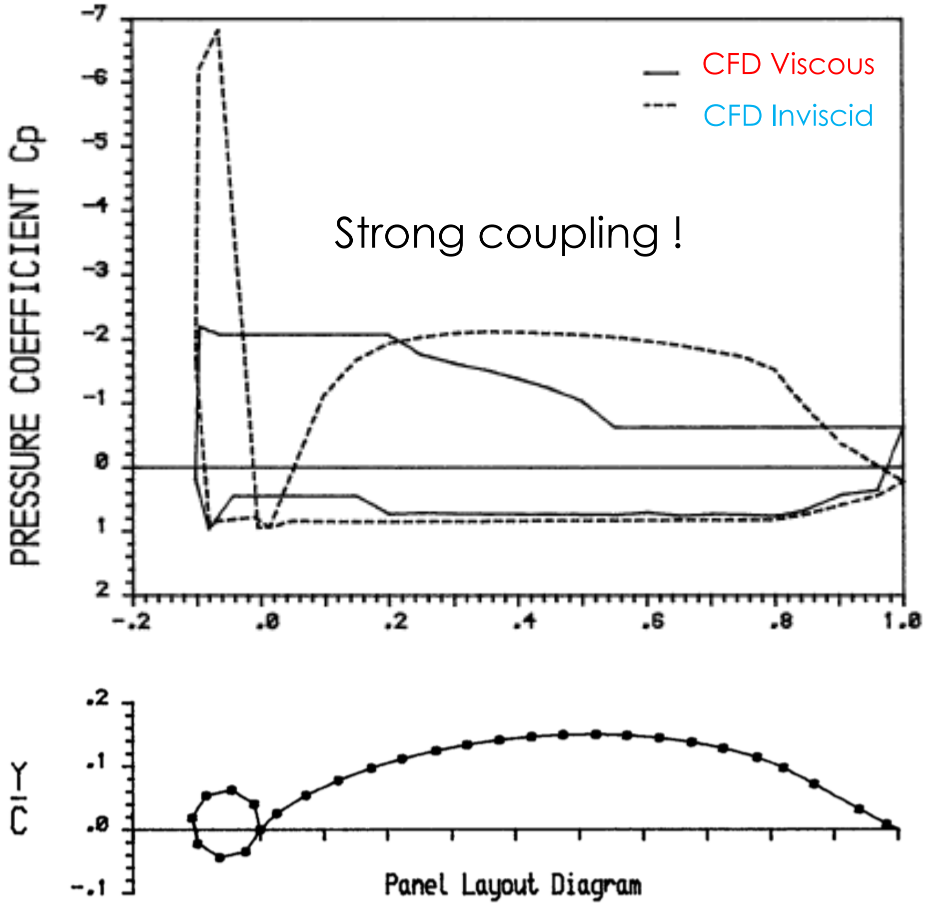
80's Mast-mainsail - EFD/CFD

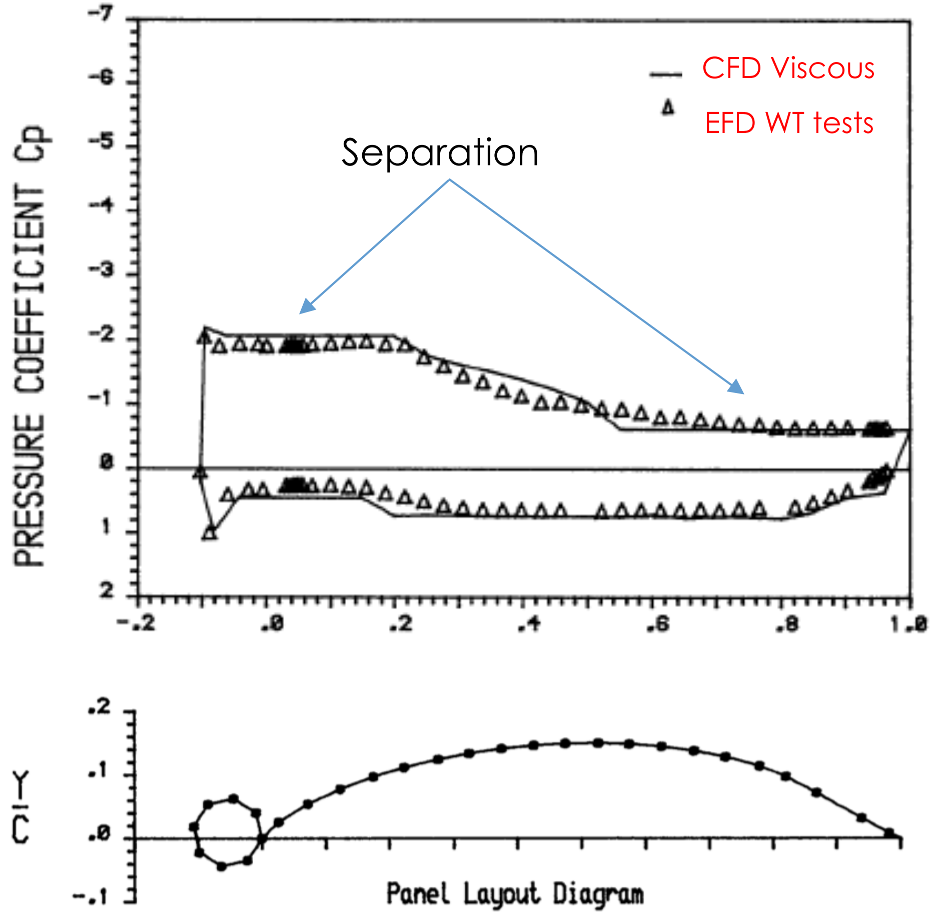
Inviscid / viscous modelling comparison



Cas 35: f/c=15%, d/c=10%, Re=10^6, a=10°

Inviscid / Viscous => **-40% C_L**





00'S MAST-MAINSAIL - EFD/CFD

Objectives:

Validation of RANS methods for separated flows

Develop an interaction model for mast-mainsail ?

Approach : WT tests & RANS

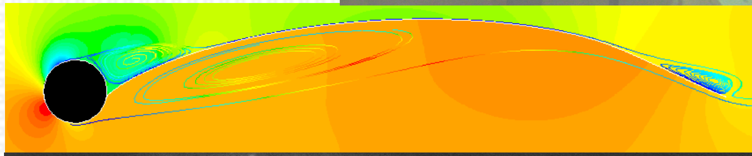
2 parameters :

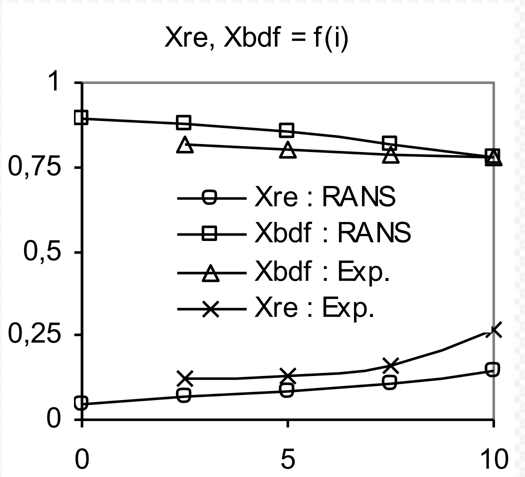
f/c sail camber [6, 9, 12, 15, 18]%

d/c mast diameter [0, 4, 8, 12]%

Best practices : mesh, numerics, …

RANS / Exp. comparisons for mast-mainsail separated flow prediction

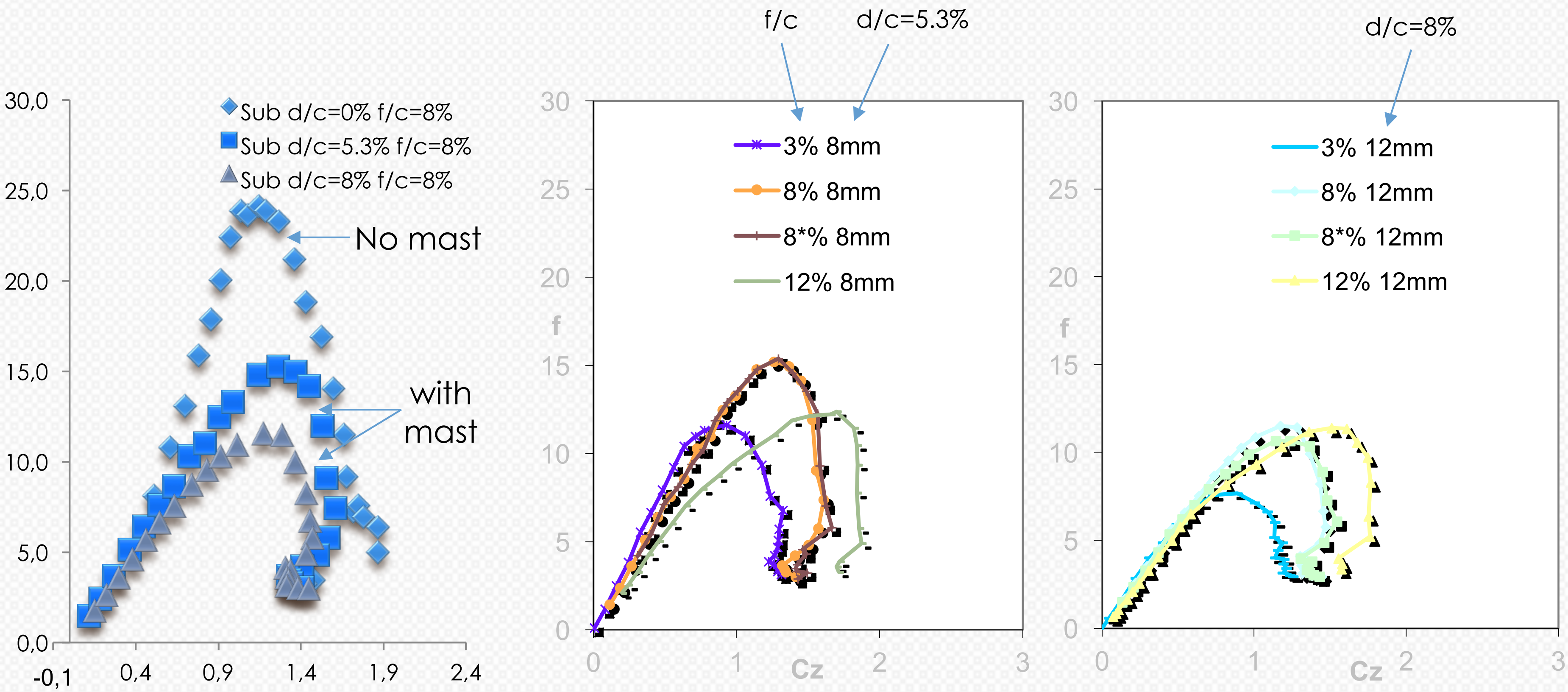




Chapin & al., Marine Technology, Viscous CFD as a relevant Decision-Making Tool for Mast-Mainsail Aerodynamics, 2005

00'S MAST-MAINSAIL - EFD

L/D variations with mast diameter, sail camber



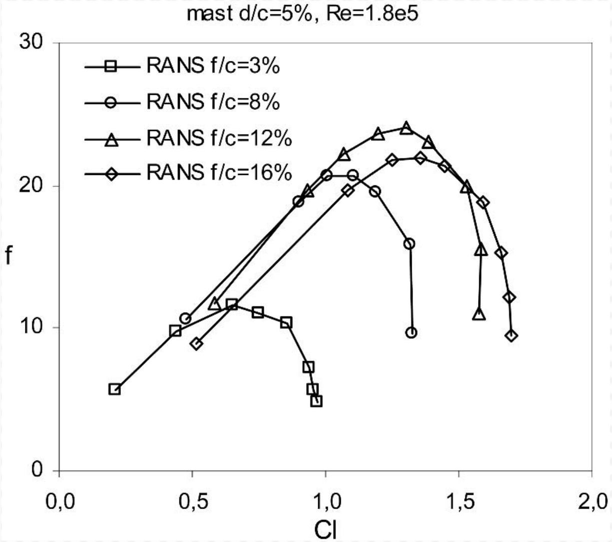
Experimental optimum camber : 8% for d/c=5%

10% for d/c=8%

Chapin & al., Sailing Yacht Rig Improvements through Viscous CFD, CSYS 2005.

00'S MAST-MAINSAIL - CFD

Optimum camber for a given mast predicted by RANS 2D
as emphasized by 3D tests of F. Bethwaite



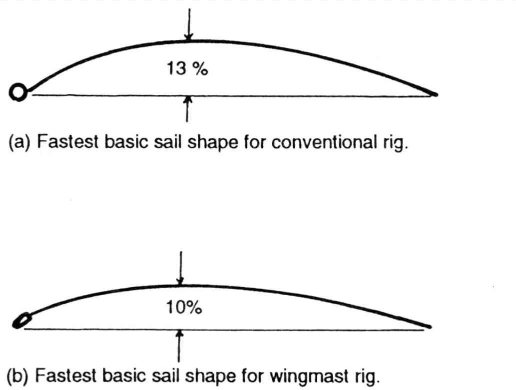


Fig 17.27 Measured cambers of championship winners

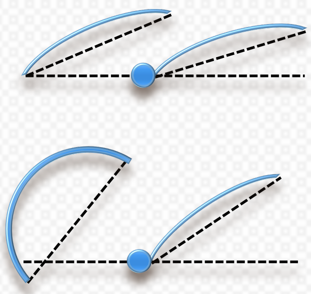
Question : optimal shapes & trim = f(AWA) ?

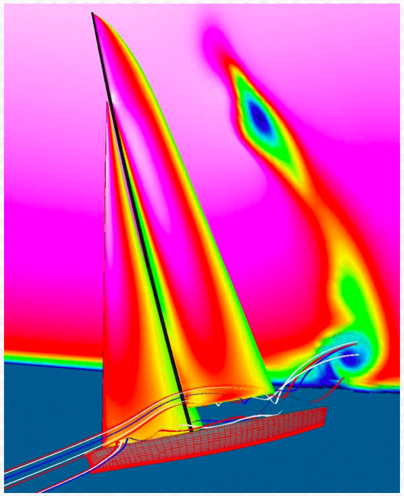
Lesson learn : « RANS able to predict performance trade-off »

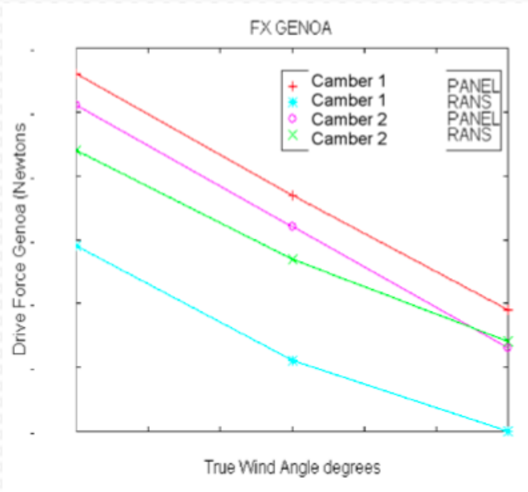
90-00-10'S MAST-MAINSAIL-JIB

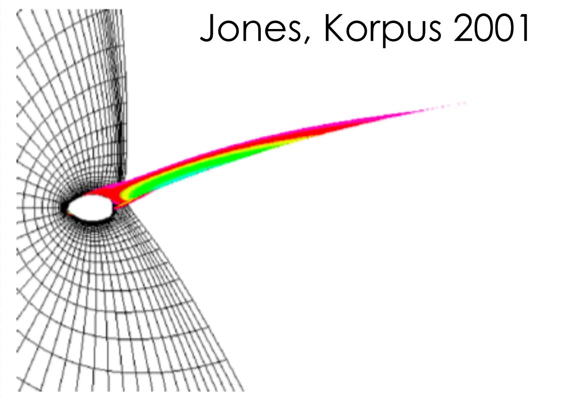
« In upwind, flow is considered attached »
=> inviscid potential

« In downwind, flow on highly cambered sails is separated »
=> viscous RANS





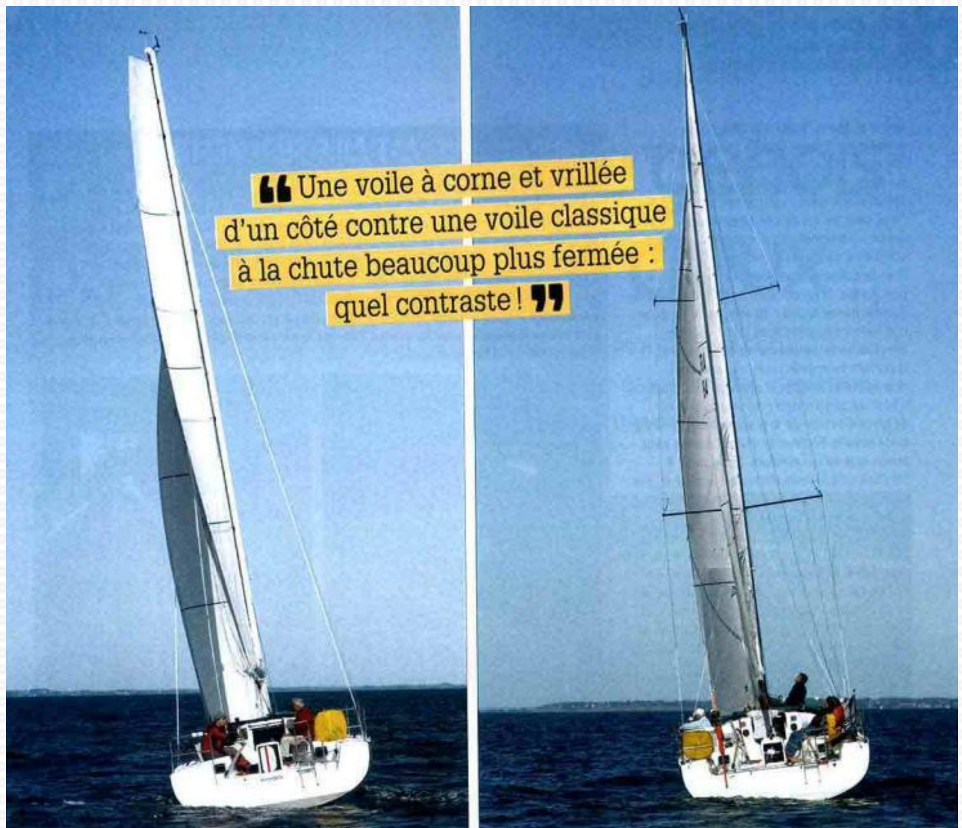




Jones, Korpus 2001

- 1996 Hedges — 1st RANS 3D - downwind
- 2001, 2004, 2007 Jones & Korpus — RANS 3D - upwind
- 2005 Chapin & al. — RANS 3D - wingmast-mainsail
- 2011 Viola & al. — EFD mainsail+jib without mast
- 2013 Viola & al. — EFD/CFD mainsail+jib without mast

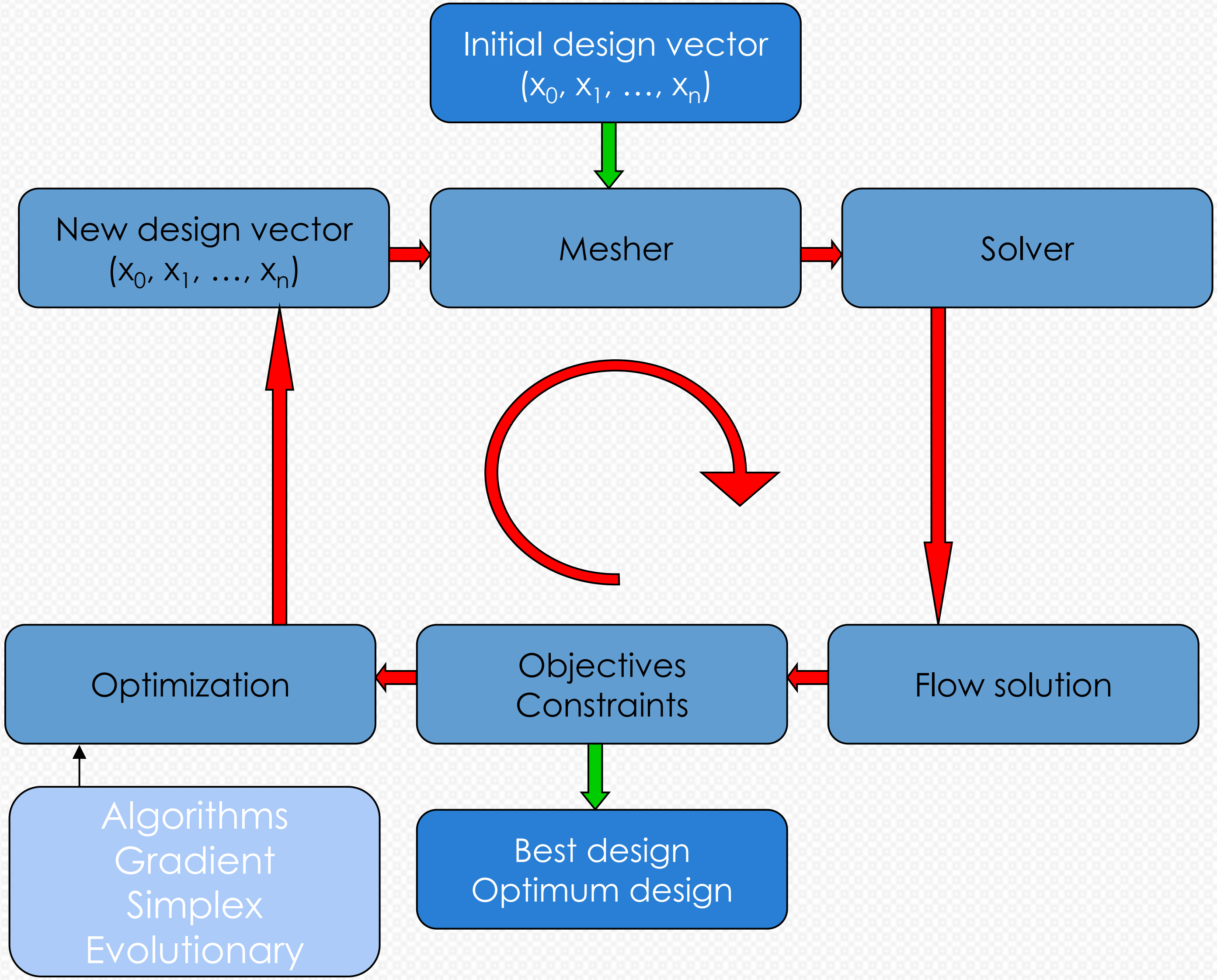
BEST SAIL SHAPES



▲ C'est l'exemple parfait du réglage de voiles. Le chariot de barre d'écoute de grand-voile légèrement au vent se traduit par un superbe vrillage de la grand-voile. De plus, la chute du génois et celle de la grand-voile sont quasiment parallèles. Ce que l'on doit toujours rechercher.

▲ Plus que de longs discours, la comparaison entre les deux photos montre bien l'efficacité de la grand-voile à corne qui utilise dans sa partie haute une surface beaucoup plus importante qu'une grand-voile classique pour aller capturer du vent fort. Par ailleurs, la grand-voile de *Mora Mora* est bien moins vrillée.

COMPUTATIONAL FRAMEWORK - CFDO

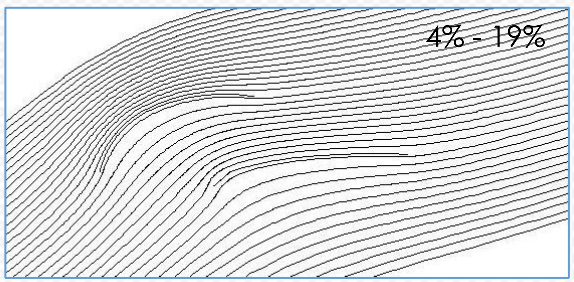


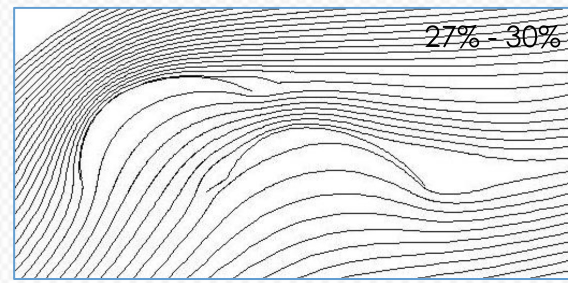
00'S - SAILS INTERACTION – CFDO

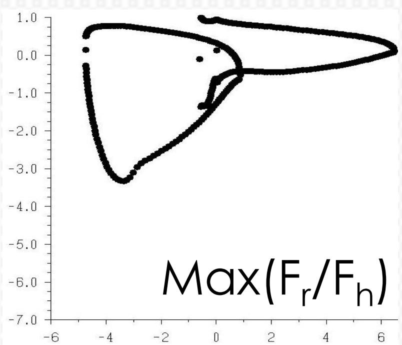
OPTIMAL SHAPE ?

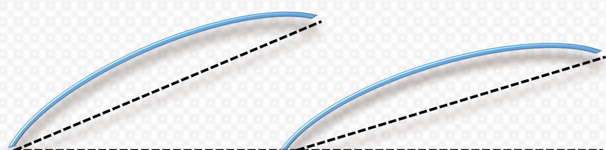
Objective function: RANS modeling
Optimization algorithms: Gradient-based or gradient-free
Shape parameterization: North Sails
Meshing new shapes: Remeshing technique
Design variables: 2 camber, 2 trim angles

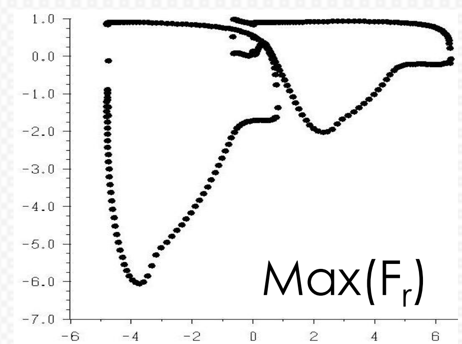
Optimum solution in 10^4 solutions ?









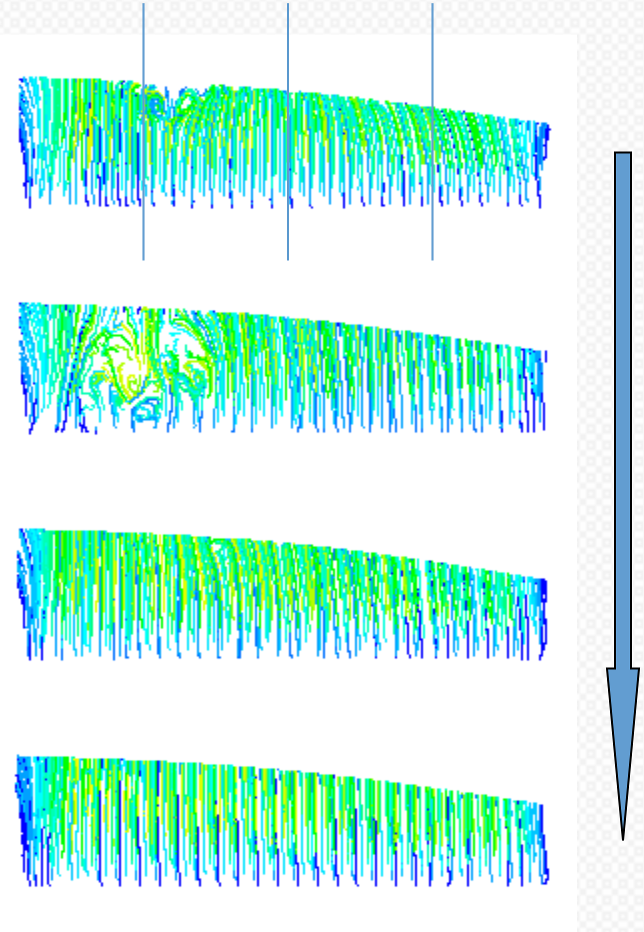


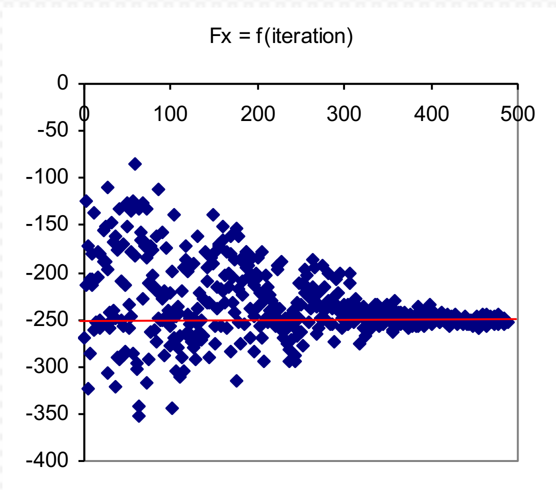
Far more interesting to be able to predict the optimum camber of interacting sails than to search for the right trim of sails with given cambers

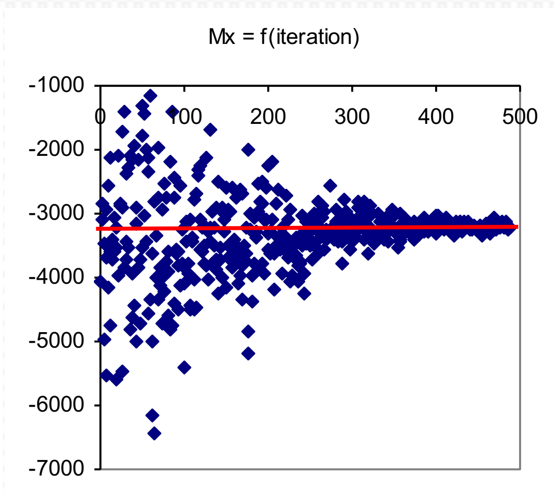
10'S OPTIMAL SAIL SHAPE - CFDO

- Aerodynamic optimal sail shape in 3D ?
  - Physics: RANS
  - Optimization: CMA-ES evolutionary
  - Param: 3x(camber, twist)
  - Objective: Maximize driving force
  - Constraint: Heeling moment
  - Convergence: Nevals=500
  - Camber: bottom ↗, tip ↘
  - Twist: decrease with z/h

$30^6 = 729\ 000\ 000$



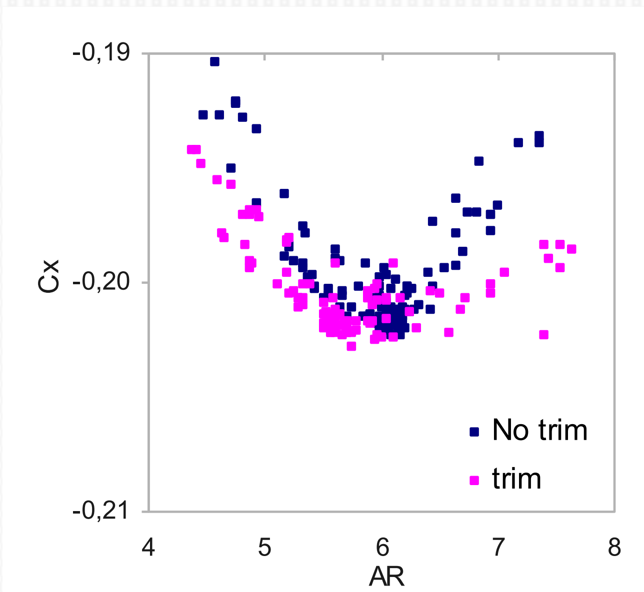


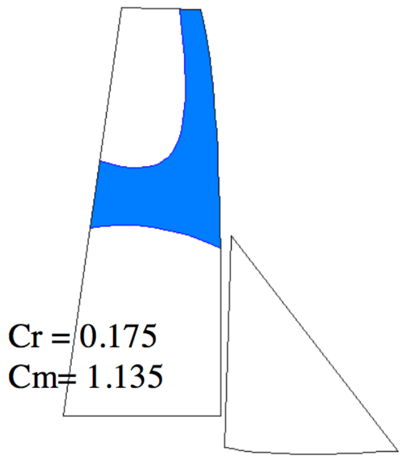


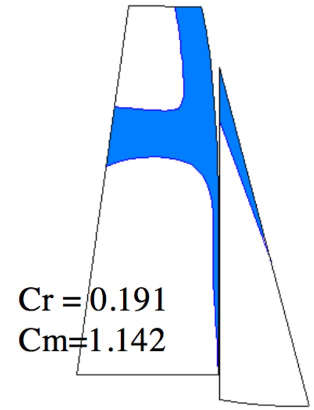
V.G. Chapin & al., Performance optimization of interacting sails through Fluid Structure coupling, IJSCT, 2011

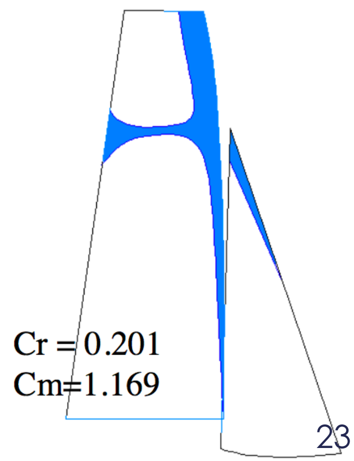
10'S SAILS INTERACTION FSIO

- **Optimum jib aspect ratio ?**
  - Physics: FSI = RANS 3D + Relax
  - Optimization: CMA-ES evolutionary
  - Param: 1 or 2 (AR, trim)







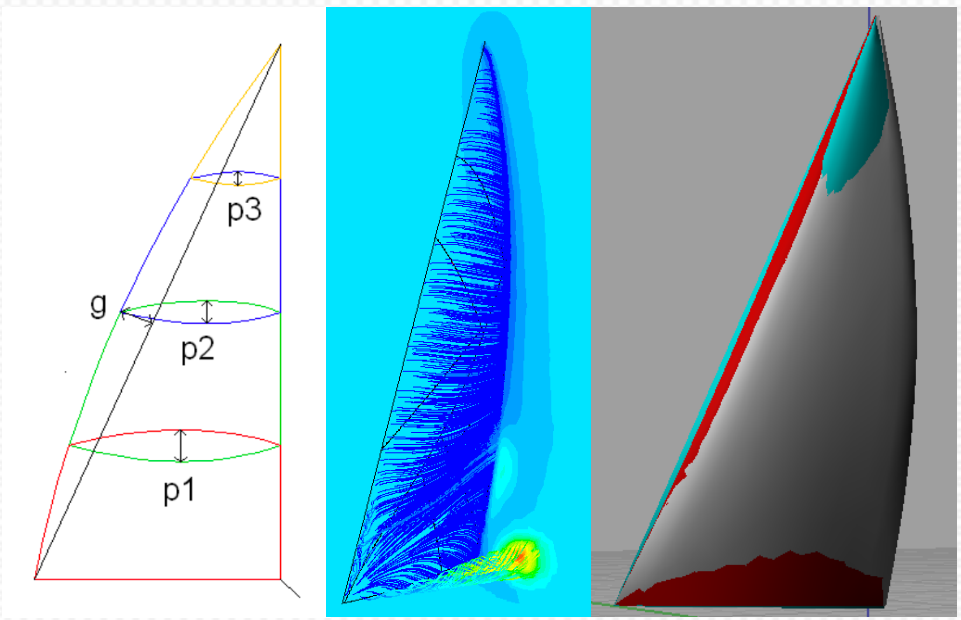


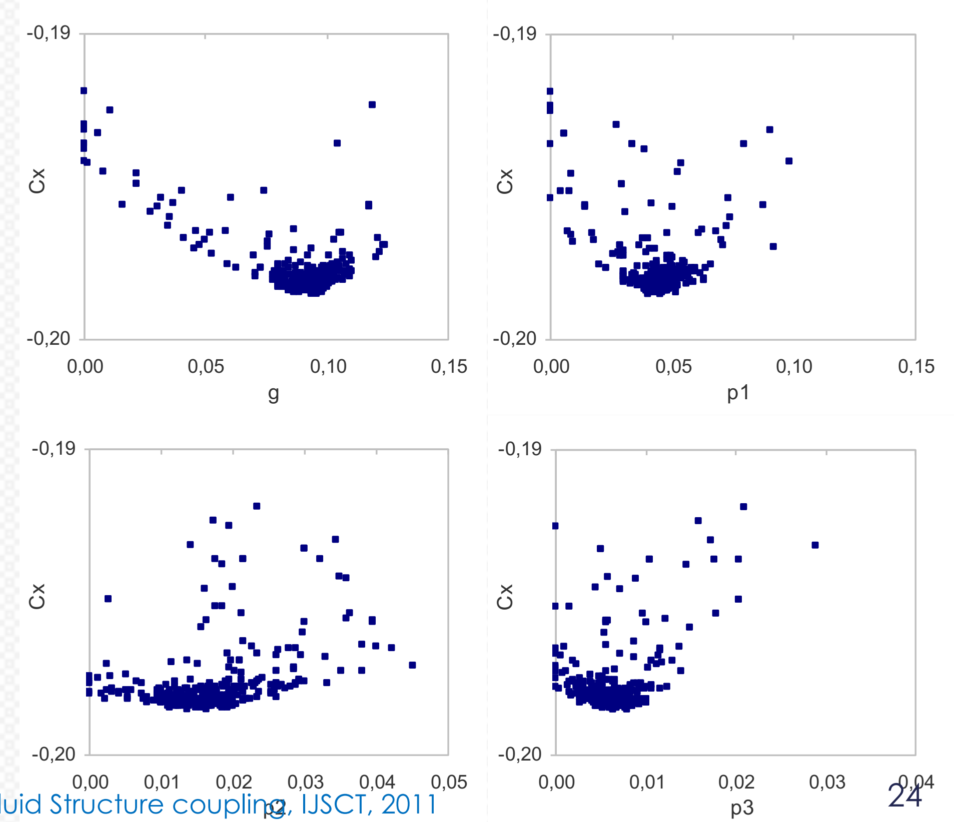
V.G. Chapin & al., Performance optimization of interacting sails through Fluid Structure coupling, IJSCT, 2011

10'S SAILS INTERACTION - FSIO

- **Optimum jib shape ?**
  - Physics: FSI = RANS 3D + Relax
  - Optimization: CMA-ES evolutionary
  - Param: seams (p1,p2,p3), luff curve g

Geo. Flow Shape





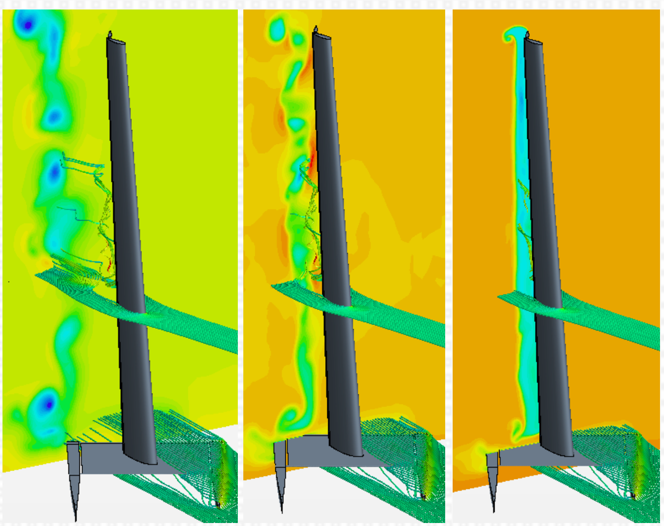
V.G. Chapin & al., Performance optimization of interacting sails through Fluid Structure coupling, IJSCT, 2011

2014 WINGSAIL - EFD/CFD

Slot flow physics (steady & unsteady)

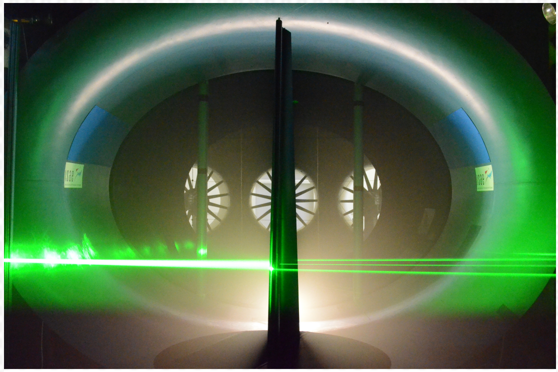
- 2014 - WT tests wingsail alone δ=15°, 25°
- 2015 - URANS, LES wingsail alone δ=15°, 25°
- 2016 – URANS, LES class C + wind gusts

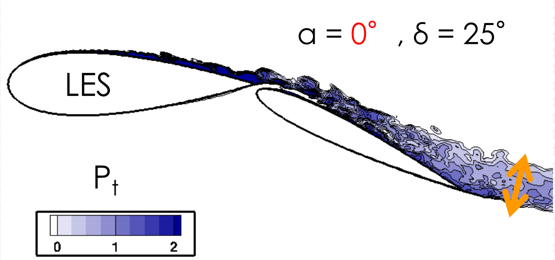
Steady wind

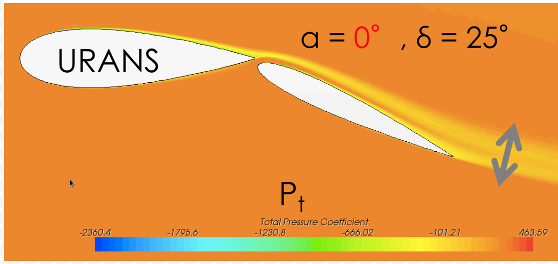


Unsteady wind

will be presented in details :



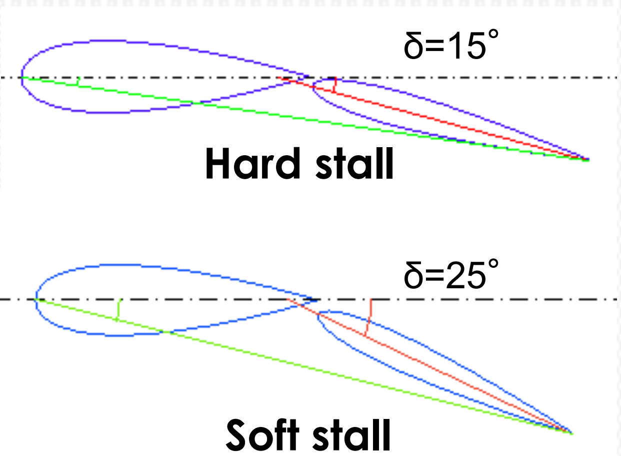




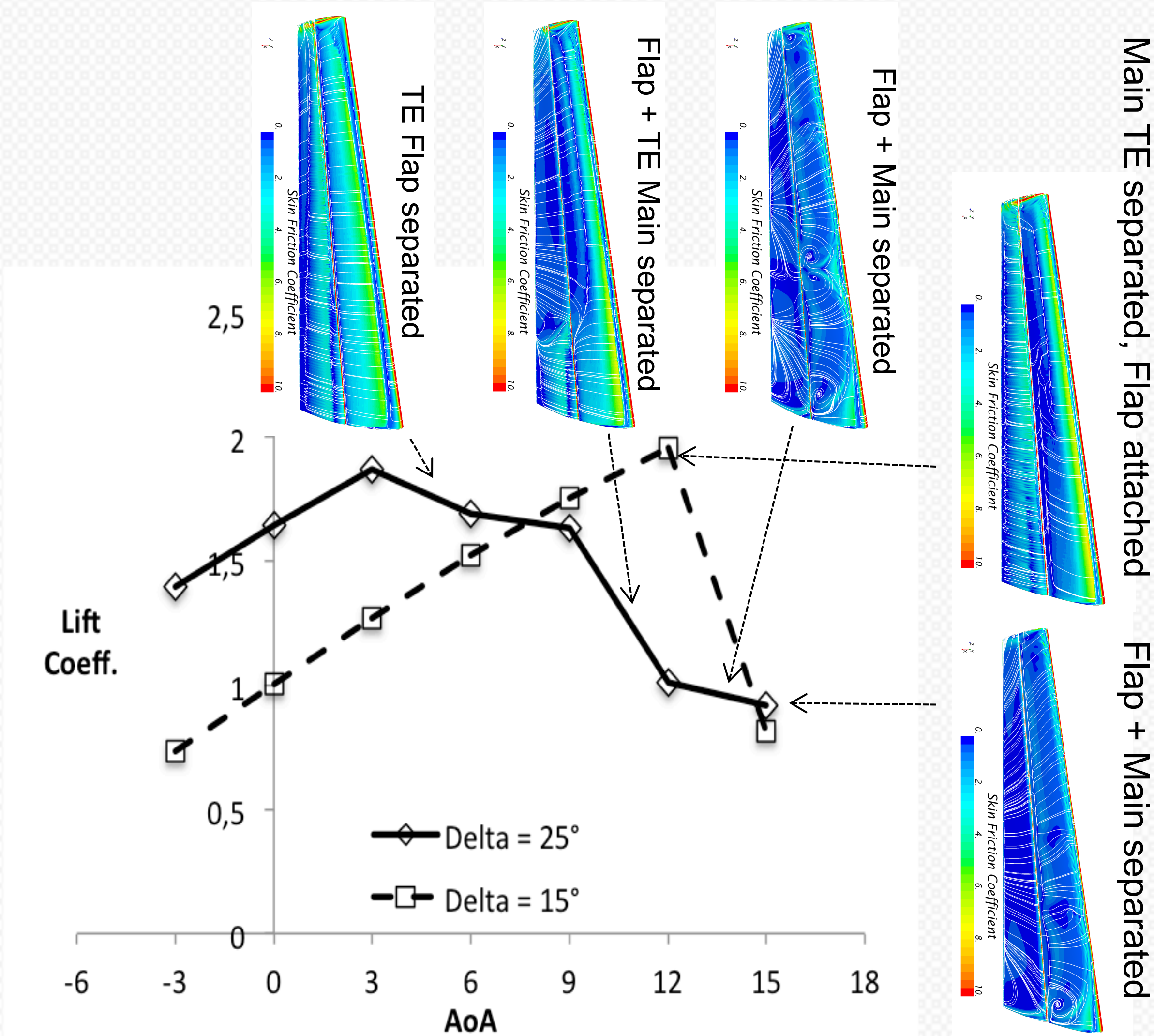
Chapin & al., Aerodynamic study of a two-elements wingsail for high performance multihull yachts, HPYD5, 2015
Fiumara & al., Num. and exp. analysis of the flow around a two-element wingsail at Reynolds number 0.53 10^6, IJHFF, 2016
Fiumara & al., Aerodynamic Analysis around a C-Class Catamaran in Gust Conditions using LES and URANS Approaches, Innovsail 2017

2015 WINGSAIL - CFD

Complex slot flow physics
3D stall characterized
Low / High flap deflection
URANS / LES comparisons



Slot optimization should be able to design better wingsails for higher performances



Chapin & al., Aerodynamic study of a two-elements wingsail for high performance multihull yachts, HPYD5, 2015

Fiumara & al., Num. and exp. analysis of the flow around a two-element wingsail at Reynolds number $0.53\ 10^6$, IJHFF, 2016

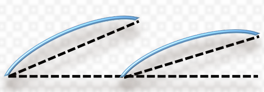
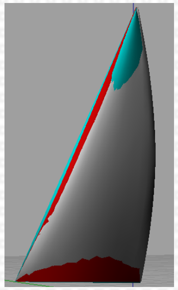
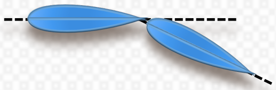
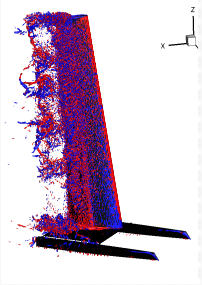
CONCLUSION

« Which is the best **flying shape** ? »

20 Curry	Nature observation	Main parameters (AR, d/c, f/c, …)
70 Gentry	Potential 2D code	Sails interaction understantind
70 Milgram	Potential 3D code – VLM	Sail & rig prediction without mast (AR)
70 Marchaj	WT tests	Mast-mainsail (d/c)
80 Wilkinson	WT Tests	Mast-mainsail (d/c, f/c, AoA, …)
00 Chapin	RANS 2D	Mast-mainsail trade-off prediction
10 Chapin	RANS 2D/3D + Optimization	Best sails shapes in given conditions…
10 Chapin	WT/URANS/LES	Wingsail 3D slot flow physics
20 …		

Nature observation, EFD, CFD, CFDO, FSIO, …
to solve as fast as possible the sail design / performance question…

Sails: from **soft** & **thin** sails to **rigid** & **thick** sails then…


Futur: « Which is the best **design shape** for given conditions ? »