Sail: Curry (1925)

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


Mast-mainsail-jib: …

Wingast-mainsail: …

Wingsail: Fiumara (2015)
...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
• 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

1993 - Bethwaite

Separation

2004 - Chapin
**70’s Mast-Mainsail**

Mast-mainsail = separated flows

**Controverse Milgram / Marchaj**
- 3D inviscid phenomenon AR
- 2D viscous phenomenon d/c

...  
1966 Herreshoff WT tests 12-Meter Yacht Mainsail Variations  
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  
...
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

L/D = 4.1
L/D = 3.4
L/D = 2.3

AR = 4.6
AR = 6
AR = 3.2

d/c = 3%
d/c = 3.9%
d/c = 2.8%

Camber \( \frac{3}{4} \) (4%) diameter of the masts 0.375”
70'S MAST-MAINSAIL - EFD MILGRAM/MARCHAJ/…

Controverse Milgram / Marchaj

1978 Milgram EFD AR, d/c effects ?
- Mainsail alone \( Cd_{2D} = f(f/c, ...) \ll Cd_i \)
- Mainsail + mast \( Cd_{2D} = f(d/c, ...) \approx Cd_i \)

\[ Cd_{\text{mast-main sail}} \neq Cd_{\text{mast}} + Cd_{\text{mainsail}} \]

2013 - IMS aerodynamic model

\[ C_{d\text{mast-main sail}} = C_{d\text{mast}} + C_{d\text{pv}} + C_{d\text{pi}} \]

The interaction between a mast and a mainsail is nonlinear!
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%
WILKINSON PHD 1984

A unique database for viscous CFD validations

A UNIVERSAL PRESSURE DISTRIBUTION

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

Pressure side:
A Laminar separation bubble
A transition and reattachment

<table>
<thead>
<tr>
<th>REGION</th>
<th>DESCRIPTION</th>
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<tr>
<td>I</td>
<td>Upper Mast Attached Flow Region</td>
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<td>II</td>
<td>Upper Separation Bubble</td>
<td>X_S</td>
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<td>III</td>
<td>Upper Reattachment Region</td>
<td>X_R</td>
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<td>IV</td>
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<td>V</td>
<td>Trailing Edge Separation Region</td>
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<td>VI</td>
<td>Lower Mast Attached Flow Region</td>
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<td>VII</td>
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</tr>
<tr>
<td>VIII</td>
<td>Lower Reattachment Region</td>
<td></td>
</tr>
<tr>
<td>IX</td>
<td>Lower Aerofoil Attached Flow Region</td>
<td></td>
</tr>
</tbody>
</table>

80’S MAST-MAINSAIL – EFD
Pressure distribution
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, α=10°
Inviscid / Viscous => -40% C_L

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

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

- 1996 Hedges
- 2005 Chapin & al.
- 2011 Viola & al.
- 2013 Viola & al.

1st RANS 3D - downwind
RANS 3D - upwind
RANS 3D - wingmast-mainsail
EFD mainsail+jib without mast
EFD/CFD mainsail+jib without mast

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

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

Jones, Korpus 2001
BEST SAIL SHAPES

"Une voile à corne et vrillée d'un côté contre une voile classique à la chute beaucoup plus fermée : quel contraste!"

C'est l'exemple parfait du réglage des voiles. Le chevalet de barre d'écoute de grand-voile légèrement ouvert se traduit par un superbe voilage de la grand-voile. De plus, la chute du génito et celle de la grand-voile sont ouvreademment souhaitables. Ce qui 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 aider capturer du vent fort. Par ailleurs, la grand-voile de Mora Mora est bien moins vrillée.
COMPUTATIONAL FRAMEWORK - CFDO

Initial design vector \((x_0, x_1, \ldots, x_n)\)

New design vector \((x_0, x_1, \ldots, x_n)\)

Mesher

Solver

Optimization

Objectives

Constraints

Flow solution

Best design

Optimum design

Algorithms

Gradient

Simplex

Evolutionary
Objective function: 
Optimization algorithms: 
Shape parameterization: 
Meshing new shapes: 
Design variables: 

RANS modeling 
Gradient-based or gradient-free 
North Sails 
Remeshing technique 

Optimum solution in $10^4$ solutions?

Max($F_r/F_h$)

Max($F_r$)

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
• 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

V.G. Chapin & al., Performance optimization of interacting sails through Fluid Structure coupling, IJSCT, 2011
**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
• Optimum jib shape?
  – Physics: \( \text{FSI} = \text{RANS 3D} + \text{Relax} \)
  – 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 $\delta=15^\circ$, $25^\circ$
- 2015 - URANS, LES wingsail alone $\delta=15^\circ$, $25^\circ$
- 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 $0.53 \times 10^6$, IJHFF, 2016
Fiumara & al., Aerodynamic Analysis around a C-Class Catamaran in Gust Conditions using LES and URANS Approaches, Innovsail 2017
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, HPYDS, 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 ? »

Nature observation
Potential 2D code
Potential 3D code – VLM
WT tests
WT Tests
RANS 2D
RANS 2D/3D + Optimization
WT/URANS/LES

Main parameters (AR, d/c, f/c, …)
Sails interaction understandind
Sail & rig prediction without mast (AR)
Mast-mainsail (d/c)
Mast-mainsail (d/c, f/c, AoA, …)
Mast-mainsail trade-off prediction
Best sails shapes in given conditions…
Wingsail 3D slot flow physics

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 ? »