HOW MULTIDISCIPLINARY SCIENTIFIC RESEARCH MAY HELP BREAK THE SAILING SPEED RECORD

M. Calmon & al., EPFL Hydroptère Design Team
Introduction

- *l’Hydroptère*
  - Lift of hydrofoils, complete balance of weight
  - Drag reduction, high performances
- Sailing speed records
  - Channel, 2005
  - Outright 500m & 1NM
  - Back to offshore
- Complex problems to solve
  - Trans-disciplinary project
  - EPFL scientific partnership
- New challenges
  - Versatility
  - Reliability
- Future projects
  - *l’Hydroptère.ch*
  - *l’Hydroptère Maxi*
Load case & sailing conditions

Local stress state at the ply level

Failure criteria

Safety limits

Performance

Material design & mechanical testing

Global deformations & vibration modes

CAD & FE Model

Design & Optimization Process

Innov’Sail 2010, Lorient, July 1st
Structure:
- Finite Element model of the structure
- Coupled fluid/structure dynamic simulation
- Experimental validation

Hydrodynamics:
- 3D CFD simulation of the foils
- Optimization / Cavitation limit
- Experimental validation

Materials:
- Safety of operation
- Weight reduction

On-board monitoring & image processing:
- Validation data, safety limits
- Sail performance, load case

Design:
- “Pushing the limits”...
- but within the limits

Collaboration Overview:
- L’Hydroptère Design Team
- LMAF
  Laboratory of Applied Mechanics and Reliability Analysis
- CVLab
  Computer Vision Laboratory
- LTC
  Laboratory of Polymer and Composite Technology
- LMH
  Hydraulic Machines Laboratory

Innov’Sail 2010, Lorient, July 1st
4 sub-systems:
- Stress & positioning sensors (HBM digiCLIP)
- Navigation unit (B&G WTP2)
- Inertial unit (IXSEA Octans)
- Video system (Cosworth Pi VIDS2)

CAN-bus

Data logger & ruggedized computer
- Cosworth Pi Sigma LLB
- Lemer Pax Posibox

Motivation
- Real-time load analysis
- Feedback on dynamic behavior
Foil Immersion Detection

- **Motivation**
  - Platform motions with reference to water surface
  - Refined foil loads
- **Measurement system integration**
  - Synchronization
Foil Immersion Detection

- **Refraction-based principle**
  - Move along the foil leading edge
  - Look for a change of slope
- **Algorithm keypoints**
  - Functional maximization
  - Kullback-Leibler divergence
    \[ F(d, \theta) = \frac{D_{KL}(P, Q) + D_{KL}(Q, P)}{2} \]
    \[ = \frac{1}{2} \sum_{i=0}^{255} P(i) \log \frac{P(i)}{Q(i)} + Q(i) \log \frac{Q(i)}{P(i)} \]
- **Hazards**
  - Changing light conditions
  - Reflections
  - Blurred images by spray drops
Cross-Beam Torsion

3D mesh and deformation using structure model behavior

3D deformed model corresponding to image

Calibration parameters

2D silhouette of 3D deformed mesh

OPTIMIZER
Fit silhouette with input image maximizing probability

Input image

Probability image
Manufacturing Processes

- Shipyard practice (Decision SA)
- Processing methods studies
  - Heating rate
  - Applied pressure
  - Draping sequence
- Part quality control
  - Micrographic visual inspection
  - Curing stage (DSC, DMA)

Sound composite

Process-induced porosity
Monolithic Parts

- Off-axis plies in thick laminates
- Role on failure mechanisms
- 4-pt bending
- Design rules
Sandwich Structures

- Behaviour identification
- Anisotropic honeycomb (Nomex Flexcore)
- Preliminary tests
  - Tension, compression and shear for the skins
- 4-pt bending
  - Several span lengths
  - Core shear modulus
- Structural model updating
Threaded Joints

- Joining metallic to composite parts
- Joint strength influenced by:
  - Stacking sequence
  - Insert
  - Screw
  - Glue
  - Thread length
- Special testing device
  - Screw pulling-out

![Images of threaded joints with various materials and testing devices.]

**Graphs:**

1. Normalised ultimate strength [%] for different types of joints, including threaded + glued, Helicoil insert, and Composite insert A & B.
2. Normalised ultimate strength [%] for threaded + glued joints with different thread lengths: 1d, 1.5d, and 1.7d.
3. Normalised ultimate strength [%] for Wet Layup and threaded + glued joints with 1d stainless screw.

Innov’Sail 2010, Lorient, July 1st
Bonding

- Joining Titanium to composite parts
- Surface treatment investigations
- Fracture strength measurements
  - Griffith’s critical strain energy release rate $G_{IC}$
- Accelerated aging tests
- Cohesive zone model in Abaqus
  - Previous fracture test
  - Extended failure criteria test
Hydrodynamic Phenomena

- **Cavitation**
  - Formation of vapour cavities in low pressure zones
  - Almost impossible to avoid with high speeds
  - Alteration of hydrodynamic performances
  - Vibrations

- **Ventilation**
  - Air from above the free surface sucked into low pressure zones below the surface
  - Drop in lift

\[ \sigma = \frac{p - p_v}{\frac{1}{2} \rho V^2} \]
Experimental Context

- **EPFL high speed cavitation tunnel**
  - 150mm square test section
  - Pressure controlled from 0.02 to 1.6MPa
  - Inlet flow velocity up to 50m/s
  - Angle of attack control
  - 5-axis balance for force measurement
  - Strobe, digital camera
  - Flash lamps, high speed video camera

- **l’Hydroptère specific tests**
  - 1/10\textsuperscript{th} scaled models of foil and rudder/stabilizer
  - Developed turbulent boundary layer (V>15m/s)
  - Adjustment for cavitation similitude above 50kt
Experimental Cavitation

- Attached cavitation
- Angle of attack dependence
- Low angles (left):
  - Long thin cavity starting downstream leading edge (sheet cavitation)
  - “Smooth” flow, low vibrations
- High angles (right):
  - Cavitation inception even for higher $\sigma$
  - Cavity detachment moves upstream until leading edge
  - Pulsed cavities (cloud cavitation)
  - Lift fluctuations, high vibrations

$\sigma = 0.25$ $\sigma = 0.80$
Simulated Cavitation

- **Numerical context**
  - 3D RANS solvers ANSYS FLUENT & CFX
  - Realizable $k-\varepsilon$ turbulence model
  - Multi-phase simulation with VOF method

- **Cavitation models**
  - Low pressure “contouring”
  - FLUENT Mixture model
  - CFX three phase flow model

- **Simulation validations**
  - Experimental tests in EPFL cavitation tunnel
  - Visual comparisons
  - Hydrodynamic loads variations

High $\sigma=0.49$ and low cavitation (—)
Low $\sigma=0.31$ and strong cavitation (—)
(- - - Simulation, — Experiments)
Simulated Ventilation

- **Numerical context**
  - 3D RANS solvers ANSYS FLUENT & CFX
  - Realizable $k$-$\varepsilon$ turbulence model
  - Multi-phase simulation with VOF method

- **Simulation validations**
  - No new experimental tests
  - Visual comparisons during sea trials
  - Bibliography test case

- **Hoerner, Fluid-Dynamic Drag, 1965**
  - Dingee experiments, 1953
  - Davidson Laboratory, NJ, USA
  - Slender surface-piercing strut
  - Loads variation according to angle of yaw
Simulated Real Case

- **Numerical context**
  - 3D RANS solver ANSYS CFX
  - Realizable $k-\varepsilon$ turbulence model
  - Multi-phase simulation with VOF method

- **Three-phase simulations**
  - Cavitation
  - Flat free surface (ventilation)
  - Steady state conditions

- **Optimization process**
  - Manual iterations
  - High lift/drag ratio
  - Low tendency to ventilation
  - Low tendency to cavitation
Foil shape optimization

- Optimization process
  - Multi-objective procedure
  - Evolutionary algorithms
  - Towards a more tolerant design

- Numerical context
  - 3D URANS solver ANSYS CFX
  - Single phase flow
  - SST turbulence model

- Test case
  - 2D hydrofoil in tunnel test section
  - Constant upstream velocity
  - Pitch motion

- Optimization parameters
  - Lift/drag ratio in nominal conditions
  - Tendency to separation
  - Tendency to cavitation
Optimization Validations

- Experimental validation
  - Lift and drag measurements
  - 2 profiles: initial, Pareto-optimal solution

- Observations
  - Qualitative agreement
  - Drag increase postponed to higher $\alpha$
  - Quantitative discrepancies
  - Drag underestimated
  - Too late stall

- Further tests
  - RANS/exp. comparisons
  - NACA0009 profile
  - Same observations

Profile drag coefficient; comparison between initial profile (●) and Pareto-optimal profile (●) (- - - URANS simulation, —— experiment)
Large Eddy Simulation (LES)

- **Numerical context**
  - OpenFOAM solver
  - Large scales of the flow
  - $\alpha=11^\circ$, $V=5\text{m/s}$

- **Observations**
  - Unsteady detached flow and vortex streets
  - From the leading edge and far before stall

- **Validation**
  - Cavitation visualization
  - PIV
  - Drag value
- Optimization simulations with HPC
  - Licensing constraints
  - Open-source software solutions (OpenFOAM...)

- Fluid-structure interaction
  - Dynamic behaviour of sandwich structures in waves (slamming)

- Fluid-structure instabilities (divergence, flutter)
  - Foil alone
  - Whole platform

- Advanced Measurements systems
  - Visual cross beam torsion finalization
  - FBGS use investigations
  - Identification and monitoring developments
  - Dynamic stability visual alarms
Acknowledgments

J.M. Bourgeon, S. Dyen, D. Moyon, D. Schmäh, R. Amacher, D. Colegrave
