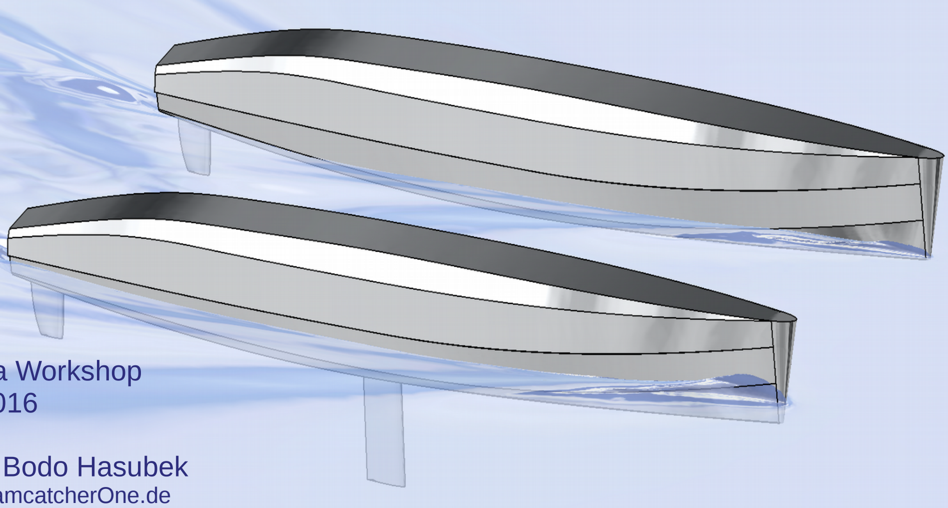
Virtual tank testing for a VPP

of a sailing catamaran



Numeca Workshop
SMM 2016

Dr.-Ing. Bodo Hasubek
www.DreamcatcherOne.de

The Project: Dreamcatcher One

A cruising catamaran for worldwide travel

Key properties

• Length	20.57m
• Max. width	10.67m
• BCB	4.25m
• Mast height	30.0m
• Sail area	270m²
• Weight	36.0t
• Material	Aluminium
• Other	Daggerboards

- Waterline length 20.17m / w bow sprit ~21.5m
- Aluminum
- Hard chines for easy manufacture without performance loss
- Developable surfaces
- Lattice mast for easy rig maintenance

- Fully equiped for independence
- Diesel electric drive system
- 230V electric system

Motivation

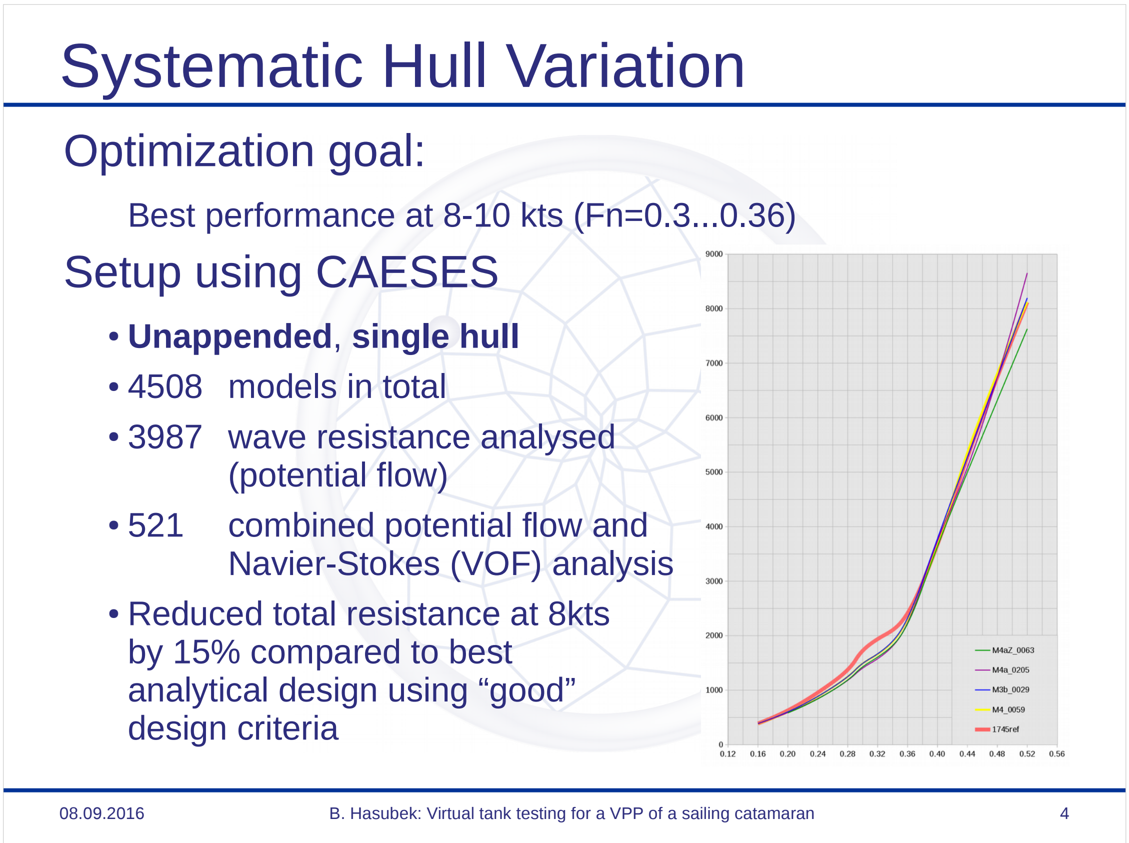
Why going through the effort of using a CFD in a yacht design?

- More realistic force calculations for optimized hull geometries
- Catamaran designs
  - Interaction between hulls can be captured (in leeway conditions as well)
  - Lift/Sinkage of hulls in heeled conditions
  - Very limited catamaran designs in Delft series
- Appendages and their interaction can be properly described

➡ More realistic performance estimate

- The common approach in yacht design is to use data from the Delft systematic series and additional modelling for heel, leeway and the appendages (ORC lines processing program (LPP))
- These are all model based approaches that rely on similarities of hull designs
- In my particular case: Large L/B, hard chined hull, optimized for a crusing speed of 8-10 knots are not properly covered by the Delft systematic series.

- independent of systematic series (Delft series)
- Commercial programs often do not cover multihull configurations and/or require hydrodynamic test data input from (virtual) tank testing
- Better control over sail model



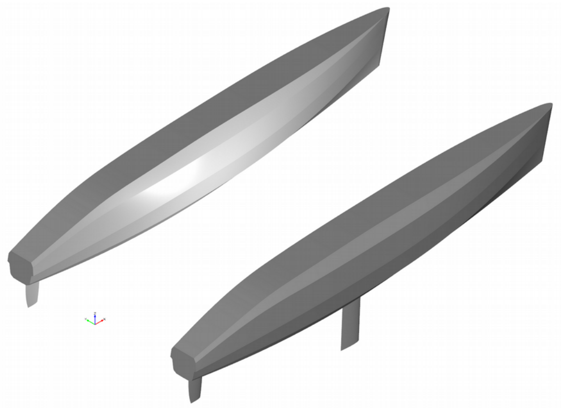
- Why am I so much interested to get results for exactly this design and not a vague approximation?
- Because of the enormous optimization effort that has flown into the design
- Systematic hull series with large variation geometric variation range:
  Fullness of bow, Length to width ratio, Width to draft ratio, width of transom, immersion of transom, ...
- Two velocities (Fn = 0.3 and 0.44 (8kts and 12kts)) were investigated to cover the main area of interest at 8ktn as well as the semi-planing area:
- Numeca Fine/Marine for the more sophisticated analyses

Model for Fine/Marine

Appended hull

- Standard profiles
  Daggerboard NACA0012
  Rudders NACA0015

- Projected areas
  Daggerboard 2.6m^2
  Rudders (each) 1.06m^2



- Asymmetric set-up with leeward board down
- Rudders are attached to hull (no gap for easier meshing)
- Rudder angle is 0°

- Areas were determined by analytical calculations based on side force assumptions

- Rudder area is at maximum distance to the daggerbords for agile navigation

- Rudders show double-elliptical shape for optimum performance

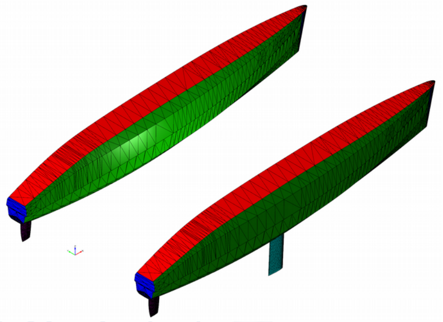
- Daggerboards are square ended for easier handling. We will see the effect of this decision later in the pressure plot.

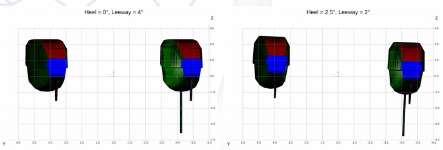
- Test simulations with rudder angles of 2° and 5° to weather showed that 2° leads to slightly reduced resistance (which is an expected behaviour known from tank tests)

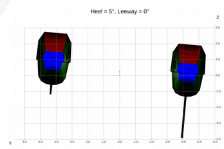
Model setup for Fine/Marine

Model setup workflow

- Parametric model in CAESES
  - Heel / Leeway transformations
  - Fixed displacement
  - Variable rudder angles and daggerboard sweep angles
- Triangulation in CAESES
  - Water-tight STL body
  - STL-triangulation exported (multibody STL)
- Different colours for different parts for automatic recognition in Fine/Marine



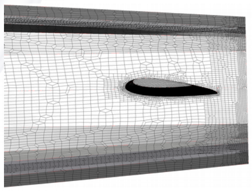




- The model is transformed by Cardan angle rotations
- The displacement is kept constant by adjusting the sink
- The model is more flexible that required for the basic tank testing. Simple parameters for:
  - Distance between hulls
  - Single or double daggerboards
  - Different sweep angles of the daggerboard(s)
  - Rudder angle is adjustable from -30° to 30°
- Triangulation in CAESES can fix invisible gaps for a 100% water tight triangulation which is mandatory for any successful meshing in Fine/Marine
- As exchange format “multibody STL” was chosen, whereby the colour names represent the different parts of the hull (hull, bow, transom, rudder, daggerboard). All, but the daggerbord are recognized by Fine/Marines setup Wizard and treated accordingly
- Using the STL format for exchange requires, that the whole model is defined as a cut-out volume of a calculation domain. Again the domain uses pre-defined colour names that are automatically recognized by the Fine/Marine Wizard
- I couldn't get the wizard to recognize the domain size, so I had to adjust it manually (in particular the width, which is pre-set to a demi-hull monohull case. This problem should be fixed in a newer version (I used V4.2)
- The wizard can generate a set of calculations for different velocities using the same mesh

Meshing in Fine/Marine

- Fine/Marine Wizard for base set-up
- Manual Mesh refinement of bow and daggerboard an rudders to properly capture sharp discontinuities in curvature
- Between 5 and 7 mio. cells (Larger number for larger heel/leeway angles)
- Grid quality measures were ruined by edge above the waterline
- Grid sensitivity analysis showed little influence on results for increased number of cells



- After the base set-up by Fine/Marines Wizard the following refinements in HEXPress were performed:
  - Sharp edges of daggerboard and rudders
  - Curved areas of daggerboard and rudders
  - Curved areas of the bow

- As can be seen in the rear view, the hull shows a sharp edge above the waterline. At the bow this edge disappears in a pointed end. The mesher does not like this kind of geometry. The cell geometry there is poor. Two conclusions:
  - Avoid sharp pointed contours
  - If it is well above the waterline and does not crash the solver, just ignore it

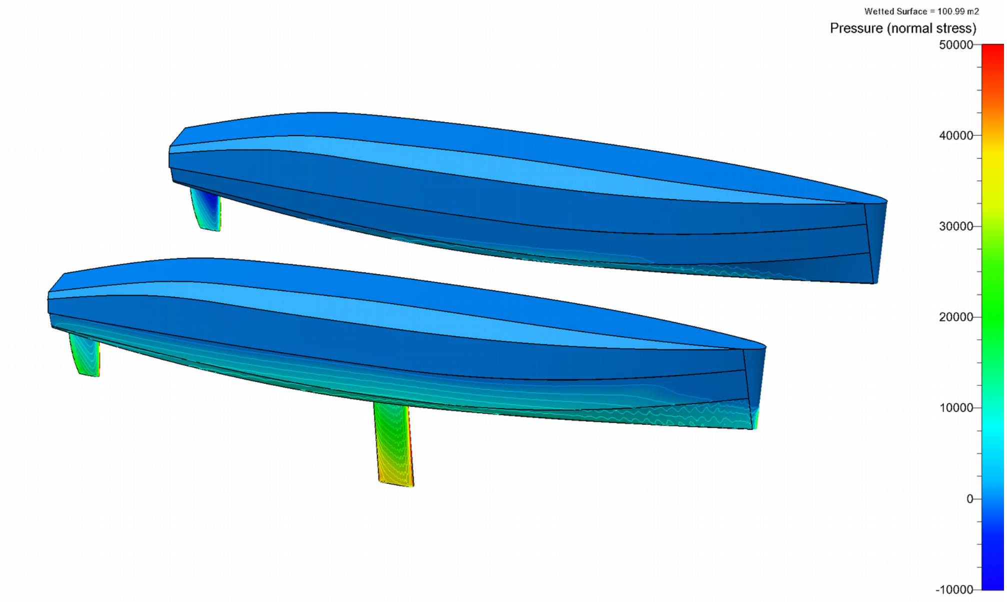
- HEXPress recognized and meshed the “normal” hard chines properly without intervention

Virtual tank tests

- Test range
  - Velocities 4-14kts (Fn=0.15-0.52)
  - Heel 0.0° – 5.0°
  - Leeway 0.0° – 4.0°
  - Total 4 velocities each
    16 models at different angle combinations
    64 calculations
- Calculation effort
  - Hardware 8-core Hashwell running at 3.0/3.5 GHz
    64 GB RAM (no swapping)
  - Average calc. time 29.1 hours (per calculation)
  - Total calc. time 77 days

- The test range was chosen with respect to the expected boat behaviour:
- Velocities: The limit of 14kts (Fn=0.52) was caused by the solver that did not appear to deliver reliable results above this velocity probably due to the semi-static solver approach I used to save calculation time.
- Heel was limited to 5°: This is about half the angle at which the leeward hull starts flying A cruising catamaran will never fly a hull. A large safety margin is required.
- The leeway for a daggerboard catamaran should never be larger than 3-4° for good performance
- The calculation effort for 64 calculation was about 77 days - An HPC cluster should be used to receive timely results.

Results: Visual inspection 1



Pressure distribution: rectangular shape vs. elliptical appendage shapes

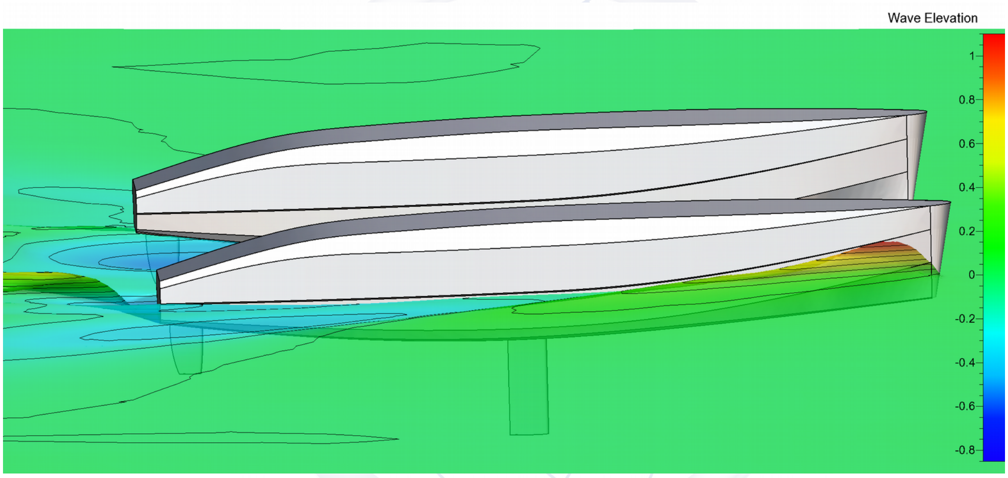
- All results show the “hard pressed” condition at 5° heel, 4° leeway and 14kts velocity

- Pressure distribution shows directly if anything did not calculate as expected.

- Interesting here: The double elliptical rudders show a very even pressure distribution which implies low losses.
- On the contrary the square-ended daggerboards show a “hot” end which intents increased performance losses there.

- The square shape of the daggerboards was chosen for easier handling and manufacturing. Comparative calculations with an elliptical shape might be interesting to evaluate the performance loss.

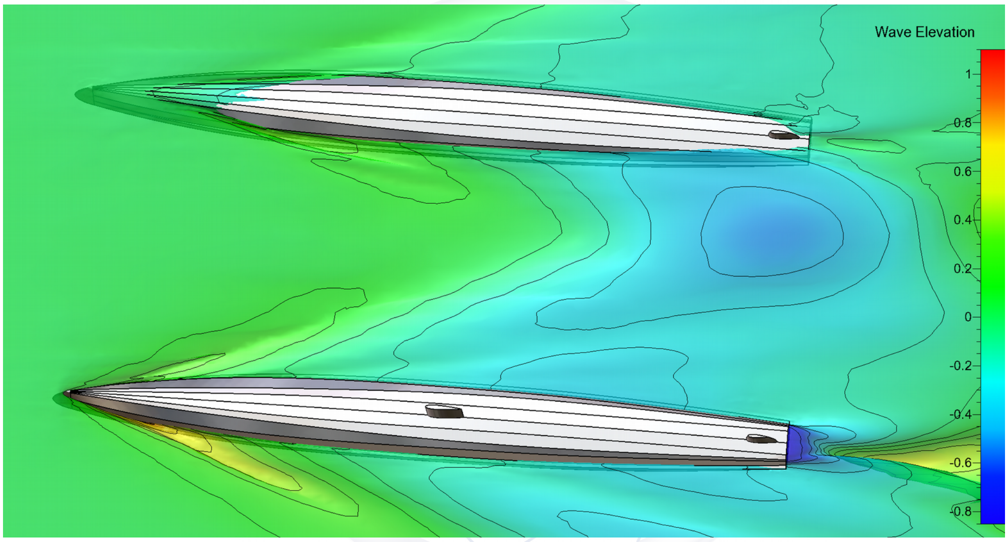
Results: Visual inspection 2



Wave elevation: Clean run-off at the submerged hull

- The wave pattern close to the hull shows a clean run-off at the transom of the submerged hull
- At least in no-wave conditions the waterline remains below the protruding edge of the hull although 28t out of 36t are displaced by the leeward hull alone.
- The waves behind the hulls are largely asymmetric in these conditions

Results: Visual inspection 3



Wave elevation: Bottom view, no rudder ventilation

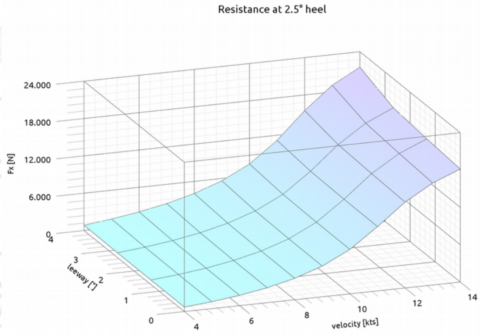
- The windward hull flies its bow

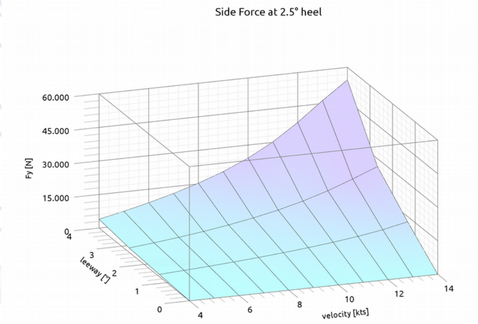
- No ventilation of the windward rudder under these conditions.
  However, in dynamic sailing conditions this might be different.
  That's why the rudder surface is chosen to be rather large: One (leeward) rudder is enough for safe navigation.

Results: Resistance and side forces

Numerical results

- Resistance forces in global x direction
  - Confirms results from systematic hull variation series: No bump at Fn = 0.3 (8kts)
  - Influence of leeway
  - One such surface for each heel angle
- Side forces perpendicular to mid-ship line
  - Highly efficient appendages
  - Side forces of one daggerboard sufficient to balance sail side forces





- For the velocity prediction the forces in moving direction (Fx) and perpendicular to the mid-ships direction (Fy*) are of interest.
- While Fx is delivered directly in the chose global coordinate system, Fy* need to be adjusted by the leeway angle.
- For each heel angle two surfaces like the ones shown can be derived from the calculations. They would be stacked on top of each other in the graph.
- However, for the velocity prediction a continuous, differentiable domain depending on the range comprising velocity, heel and leeway is required.

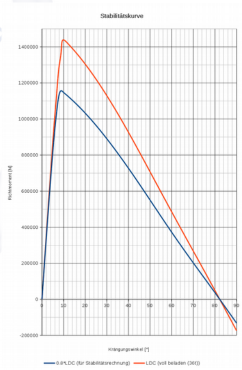
- Traditional VPPs take short cuts here.

Velocity Prediction Program (VPP)

Balancing of hull and sail forces

- ORC only uses two (equations (1) and (3))
- Here Fy-equilibrium (2) is used in addition to determine leeway angle
- CFD calculations deliver Fx and Fy, static stability curve delivers Mx of the hull
- Sailmodel delivers Fx and Fy of the sails, and the heeling arm to determine Mx
- Balancing is done using the Newton-Raphson-Method

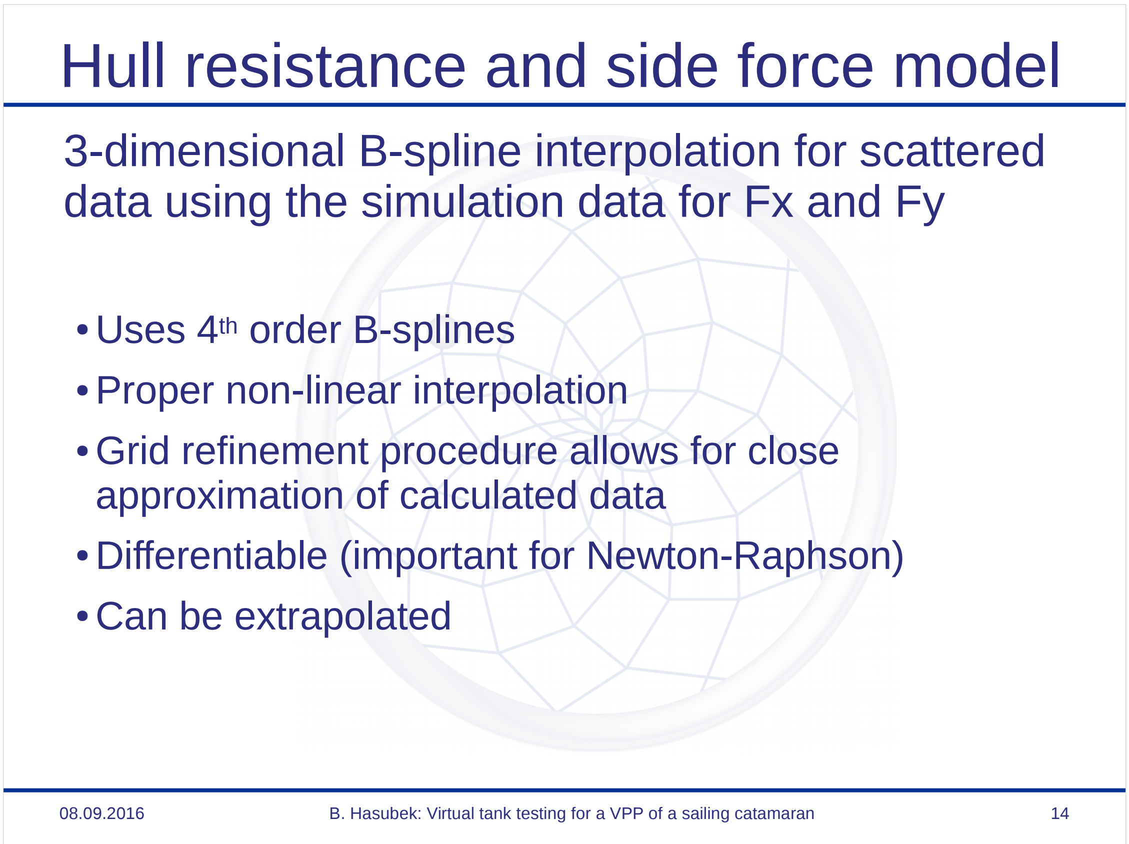
$$F_x^A = F_x^H \quad (1)$$
$$F_y^A = F_y^H \quad (2)$$
$$M_x^A = M_x^H \quad (3)$$



How is this data used in a VPP application?

A SHORT OVERVIEW

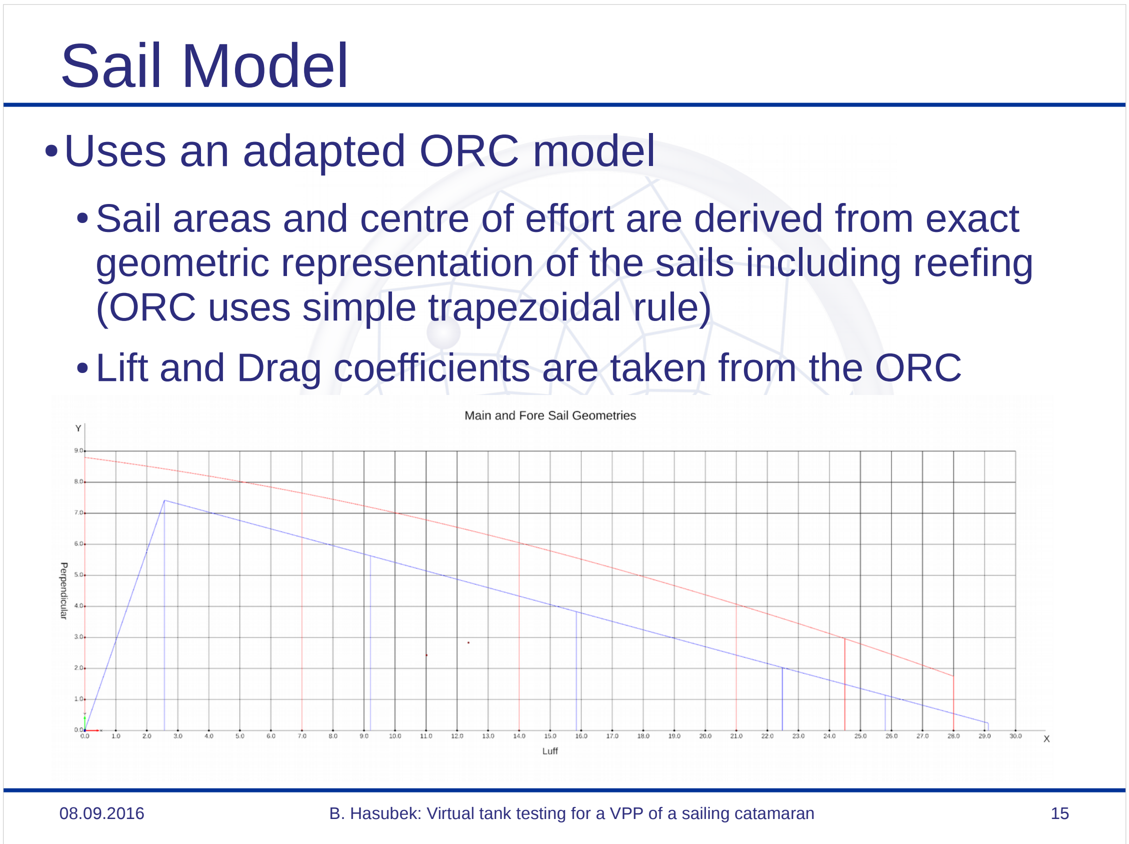
- Generally 6-dof (Fx, Fy, Fz, Mx, My, Mz)
- However, traditional VPP only uses resistance forces (Fx) and heeling moments (Mx)
- For proper leeway calculations I also use the side forces (Fy) (since I have it from my CFD calculations anyhow)
- Mx of the hull is taken from the static stability curve
- The sailing model delivers Fx, Fy and the vertical center of effort to determine the the heeling arm for the sail side force Fy
- Force/Moment balancing is done with the Newton-Raphson-Method. That's the reason why I said earlier that we need a continuous and differentiable domain representing the virtual tank testing results.



How can one derive a continuous and differentiable surface for the virtual tank testing results?

- There is a N-dimensional B-spline interpolation method for scattered data (see Lee; Wolberg et al.: “Scattered data Interpolation with multileven B-Splines, IEEE, 1997)
  - that uses 4^{th} order (3^{rd} degree) B-splines
  - that are two times differentiable (C^2 continous)
  - that allows for close approximation of scattered data points using a refinement procedure

- As a bonus the values can be extrapolated a little bit with good accuracy (if it turns out that the calculated range was a bit to small)



- The area of sail force modelling dates back to to the 1970ies when Kerwin (1978) presented a first analytical rig model for a VPP using one set of lift and drag coefficients for the complete rigg.
- Hazen (1980) separated the sail areas (fore, main, spi, mizzen) and treated them with independent lift and drag coefficients.
- This procedure is more or less still used in the (Offshore Racing Council) ORC VPP. The coefficients change regularly, the geometry of the sails includes roach etc.
- I follow the ORC approach with some improvements in sail area calculation and amendments to the reefing procedure (due to my small self-tacking jib)
- I am still waiting to see the ORC VPP Documentation 2016 which undergoes a major re-write at the moment and will hopefully correct or clarify all the issues I mailed to the author in spring.

Advantages/Disadvantages

Advantages

- Arbitrary hull shapes
  - Multihulls
  - Hard chines
- Independent of systematic series
- Unusual appendage configurations
- Bonus: Moments around vertical axis for boat balance considerations

Disadvantages

- Only flat water simulation (no waves)
- Calculation effort

Thank you

Questions?

More information on my project:

www.dreamcatcherone.de (German only)