Shape optimization of a ship based on CFD simulations

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- Overview of DCNS Research CFD activity
SIREHNA is now part of DCNS RESEARCH

There is a need to increase the CFD capabilities:

- Growing of the team: switch from 2/3 engineers to 7/8 engineers
- Growing of the computing resources: switch from 8 cores to 144 cores
- Growing of CFD code capabilities: benchmark of codes (Fluent, FINE/Marine, STAR-CCM+, …)

CFD code benchmark was beneficial to STAR-CCM+, but a case study was necessary to confirm, … that is what is presented in the next part of the presentation
Case study: shape optimization of a monohull fishing vessel

- Shape optimization of a monohull fishing vessel based in particular on CFD calculations

- From a given monohull (24 m long), the objective is to modify the shape to:
  - minimize its resistance (given displacement and target speed)
  - maximize seakeeping qualities (accelerations based criteria)
  - respect geometrical constraints (internal fitting, stability)
Case study context

- Hull shape optimization performed in the scope of the French maritime project COCHISE (design of a new type of trawler)

- Initial and derived hulls: industrial properties of the naval architect Bureau MAURIC

- Example of multi-objective and multidisciplinary optimization on an industrial case with industrial tools (CATIA, STAR-CCM+)

- Part of the optimization and calculation activity performed within the OMD2 research project (ANR project dealing in particular with multi-disciplinary optimization methods and associated technologies, applied on industrial applications requiring heavy calculations)

- Optimization including extensive CFD simulations → use of a grid for the distribution of the simulations (PACAgrid HPC Hardware)

- Multi-level approach: two levels for flow simulation → potential and viscous codes

- Use of specific technics to reduce calculation time: initialization of CFD calculation with the results of already calculated closest solution, use of response surfaces…
Tools used

- CATIA v5: parametric CAD model
- AQUA+: seakeeping calculation
- REVA: potential ship resistance calculation
- STAR-CCM+: viscous calculation of ship resistance
- modeFRONTIER: optimization environment
Optimization problem definition

2 objectives:

• Minimize ship resistance (at 10 knots for a given displacement)
• Minimize accelerations at a rear point (seakeeping criterion)

Constraints

• constant overall length (LOA)
• waterline length < max. value
• constant displacement
• constant longitudinal CoG
• GM > mini. value

Geometrical parameters

• 6 general parameters + 4 bulbous bow parameters
Global geometrical parameters (without bulbous bow):

- Overall width of the ship
- Stern width
- Entry angle in water
- Stern bottom angle
- Wedge length
- Wedge height

Local geometrical parameters (with bulbous bow):

- Longitudinal position of the bulb
- Bulb height
- Bulb nose altitude
- Bulb width
Optimization strategy: multi-level approach

Two level approach to reduce calculation times

Level 1:
Global optimisation
(without bulbous bow)

- 2 objectives: resistance and seakeeping
- Global parameters only
- Seakeeping objective computed with AQUA+
- Resistance objective computed with STAR-CCM+

Level 2:
Local optimization
(bulbous bow)

- 1 objective: resistance
- Local parameters (bulbous parameters)
- Resistance objective computed with REVA

(valid because only fore part is modified and low impact on seakeeping justify the suppression of seakeeping objective)

Shape finalization by naval architect
Level 1 (global opt) : Seakeeping objective calculation (AQUA+)

Seakeeping criterion : combination of roll and pitch accelerations in a rear point of the ship, for sea state 4 and 2 wave directions at zero speed

Steps:

• Meshing of the hull with STAR-CCM+ (surface triangular mesh)
• Calculation of the transfer functions with AQUA+ (linear frequency-domain tool)
• Combination of the transfer functions with the defined wave spectrum → motion response spectrum
• Calculation of the accelerations and combination of the different terms → seakeeping criterion
**Level 1 (global opt)**: resistance objective calculation (STAR-CCM+)

- Solving of the full viscous flow problem with STAR-CCM+
- 3D Grid: refinement of relevant areas (boundary layer, free surface), $1.5 \times 10^6$ cells for ½ ship
- Unsteady calculation VOF (Volume Of Fluid) with flat wave
- Model fixed during initialization step, then progressive release of trim and heel degrees of freedom (DFBI rotation and translation motion)
- RANSE k-omega SST turbulence model
- Propeller force $F_z$ and torque $M_y$ updated from forces reports during simulation
**Level 1 (global opt):** resistance objective calculation (STAR-CCM+)

- Initialization of the calculation with the results of the closest already calculated solution
- Stopping criterion on the resistance
- CFD calculation over 12 CPU of PACAgrid → around 10 h per design
Level 1 (global opt): resistance objective calculation (STAR-CCM+)
Level 1 (global opt) : optimization workflow

- Input variables
- Geometry generation - CATIA
- Mesh generation – STAR-CCM+
- Seakeeping calculation AQUA+
- CFD calculation STAR-CCM+
- Objectives
Level 1 (global opt) : global optimization results

Level 1 : global optimization

1st step: DOE creation

→ Correlations between design variables and objectives

Predominant parameters on the resistance: entry angle in water and stern width

Predominant parameter for seakeeping: ship width

more than 100 designs computed

2nd step: response surfaces creation
3rd step: optimization

- Virtual optimization from responses surfaces
- Use of a multi-objective genetic algorithm
- It leads to the Pareto front
- Real checking of some points belonging to the Pareto front

Results:
- reduction of 20% of the resistance for the best design in term of resistance
- reduction of 10% of the acceleration for the best design in term of acceleration
Level 2 (local opt) : resistance objective calculation (REVA)

- **Ship resistance criterion**: ship resistance at 10 knots, for a given displacement

- Ship resistance =
  - pressure resistance by potential flow code (REVA) +
  - frictional resistance (ITTC57 formulation)

- Method not accurate enough to correctly address stern shape variations → approach used here to address only bow shape variations

- Interest: very short calculation time compared to CFD RANSE methods used for the global optimization

**Steps:**

- Meshing of the hull surface with STAR-CCM+ (triangular surface mesh)
- Calculation of wave resistance (REVA) + addition of the ITTC57 resistance
Level 2 (local opt) : results of ship bow optimization

- Addition of a bulbous bow at overall length constant (increase of the bow angle)
- Addition of the bulb effective in term of resistance only if the direct profit of the bulb offsets the loss related to the reduction of the waterline length
- The global design parameters are fixed to the values obtained during the first level optimization (those of the best design in term of resistance)

- The replacement of STAR-CCM+ (Navier-Stokes) by REVA (potential) for resistance calculation checked for some designs → good results (similar ranking)
Level 2 (local opt) : results of ship bow optimization

Optimization strategy :

- creation of a first DOE to explore design space
- then creation of response surfaces to realise virtual optimization
- best virtual designs checked (REVA and STAR-CCM+ simulations)

Results :

Predominant parameters are bulb height and longitudinal position of the bulb → bulbous bow the longest and the closest to the free surface

- Additional reduction of the resistance of 5% for the shape with bulbous bow compared with the shape without bulbous bow (in spite of the reduction of the floating length)
- Total reduction of the resistance of 25% compared to the initial shape
Finalization of the optimized geometry

Final optimized shape improved by the naval architect (Bureau MAURIC) to obtain a “clean” solution consistent with some additional criteria

The impact of these modifications not covered by the parametric model (and therefore not accessible by the optimization process) checked by CFD simulation with STAR-CCM+

→ Additional reduction of 8% of the ship resistance

→ Total reduction of 33% of the ship resistance compared to the initial shape
Verification: experimental tests and numerical simulations

- Experimental model of the final geometry (scale 1/12) built and tested in basin to check the performance

- Numerical CFD simulations corresponding to model tests conditions done for comparison

- The comparison calculations / model tests is excellent
Conclusions

• Significant **reduction of around 33% of the ship resistance** from initial shape without a bulbous bow → final shape with a bulb

• Validation of the approach of **design optimization** based on shape variations with heavy simulations. Use of particular strategy and methods to minimize calculation time:
  - two-level optimization approach – (global with Navier-Stokes, local with potential flow)
  - reduction of CFD simulations runtime (closest design restart, stopping criterion)
  - use of response surfaces, etc.

• RANS methods can be used to calculate ship resistance in a maritime industrial context

• STAR-CCM+ results **validated against experimental data** (measured in towing tank) and shown an excellent accuracy

• Importance of combining good levels of expertises in several domains – hydrodynamics, flow simulation, numerical optimization and naval architecture – in order to get such efficient results
Case study acknowledgements

- Fishing vessel designed by the naval architect **Bureau Mauric**

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Other DCNS Research Activities

- **Numerical towing tank**
  - resistance of submarines, underwater / on the surface
  - seakeeping: damping coefficients, forced oscillations
  - maneuverability (self-propelled with appendage, gyration)
  - submarine course stability

- **Parametric design of submarine shapes**

- **UUV approach**
  - Forced motion, use of morpher and remeshing
Other DCNS Research Activities

- **weapon launching**
  - some first trials with forced motion, sliding grids
  - next step: free motions

- **River crossing vehicle**
  - low water depth simulations, very complex blunt shapes