Hydrodynamic Drag Minimization of Ships

Adjungierte Turbulenzmodelle zur Hydrodynamischen Optimierung von Schiffe

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In Short

- About 90% of the worlds movement of goods is handled by ship.
- A major potential for reducing the environmental impact of ships is in shape optimization.
- Efficient algorithms are required for the application of shape optimization in the ship building industry.
- A precise problem formulation and consideration of constraints is crucial to obtain feasible solutions.

Because of the low cost for the transport per tonne and kilometer as well as the ability of transporting a vast amount of goods the majority of haul capacity is by ship. In 2019 the world merchant fleet compromised about 55,655 vessels [1]. The transport sector imitates about 25% (8,258 Mt in 2018) of the total CO_2 emissions world wide. Even though, the share coming from ships only is approximately 2% to 3% regarding the transport sector, the amount of 218 Mt is significant [2,3]. Efforts in all areas of the maritime industry are necessary to meet the goal of the *International Maritime Organization* (IMO), namely reduction of the green house gas emissions by 50% compared to 2008, while the demand is increasing. With shape optimization the reduction of hydro dynamic drag can contribute. The contribution through shape optimization can be via minimization of the hydro dynamic drag for newly build vessels. The hydro dynamic drag force has direct influence on the fuel consumption of a ship which in turn accounts for about 50% of the operational cost. Hence, the reduction of drag also plays an important role for economic aspects when developing new ships.

Project O2 is part of the Research Training Group RTG 2583 'Modeling, Simulation and Optimization of Fluid Dynamic Applications' at the interface between applied mathematics and computational engineering. The research involves nine teams from mathematics, meteorology, and engineering from two Hamburg universities (UHH, TUHH) and is funded by Deutsche Forschungsgemeinschaft. The focus is on development and implementation of efficient descent methods for optimization problems with partial differential equation (PDE) and geometric constraints. The investigated methods are based on optimal control theory for PDEs, transformation of Lipschitz domains and the numerical solution of the Reynolds-Averaged Navier-Stokes (RANS) equations with a Volume of Fluid (VoF) approach for free surface flows considering a two equation k-ω turbulence modeling. In this compute project the solver FreSCo$^+$, developed at the Institute for Fluid Dynamics and Ship Theory (FDS) at the Hamburg University of Technology (TUHH), is improved. Therefore, novel methods for fluid dynamic shape optimization are implemented in the framework of an efficient and robust finite volume code.

Aim of fluid dynamic shape optimization is to find the geometry of an obstacle located in a flow domain, or the flow domain it self, which is optimal regarding a particular property, i.e. minimal drag resistance for a ship hull. Therefore a given domain is successively deformed until the optimal shape is found and the shape optimization algorithm is converged. The choice of the shape optimization procedure heavily depends on how a shape is described. In general one can not assume that a parametrization, and thus an explicit description, of the domain is available as it may be the case in a CAD framework. In a CAD-free description, e.g. via a computational mesh, the domain is made variable by introducing a deformation vector field. This allows the definition of shape derivatives and the formulation of optimality regarding the objective function.

For the shape optimization problem, based on the theory of optimal control of PEDs, the variable is split into a state and a control variable. Then the state is the solution of a system of PDEs and the control is given by the domain where the state is defined on. The minimization problem is formulated as constrained optimization problem with PDE constraints which is handled by the so called adjoint approach. This method allows to derive an explicit expression for the shape derivative of the objective function from which the deformation field is extracted. Moreover, the problem contains geometric constraints in order to exclude trivial or unfeasible solutions.

For an efficient algorithm it is desirable to obtain the deformation field which leads to a fast converging shape optimization procedure while the set of feasible solutions is as large as possible. Therefore the deformation field is characterized by the steepest descent direction in the space of Lipschitz transformations. However, the computation of Lipschitz transformations is demanding and therefore a p-Laplace relaxation is considered [4]. This approach has advantages over previously used methods regarding the speed of the descent method, the appearance of the actual solution and preserving the quality of the computational mesh.

Handling of geometric constraints, however, is challenging as these constraints are of a different type than the PDE constraints. Other then the PDE constraints the geometric constraints account for a global property of the domain rather than a local property of the fluid dynamic state. In addition, the descent method used in this project is based on first order optimality conditions which do not give an expression for the multipliers associated with the geometric constraints. Therefore an augmented Lagrange-like method of multipliers was developed in [5] to account for geometric constraints with dependency on the fluid dynamic state. Numerical experiments have been carried out considering the MOERI Container Ship (KCS) shown in Figure 1. It was possible to reduce the drag resistance for smooth water conditions for more than 4% while the geometric constraints are met up to the prescribed precision of 10^{-6}. However, the geometric constraints investigated do not fully reflect the reality when thinking of free-floating bodies. If for a floating vessel, the displacement is constant throughout the optimization procedure, this prevents the hull from immersing deeper due to the hydrostatics of the hull. This does not take the heave (dynamic sinkage or vertical motion) into account due to the change in hydrodynamics. The same is regarding the center of buoyancy which prevents the ship from trimming (difference in depth between bow and stern of a ship). The pitch (dynamic rotation about the horizontal transverse axis) of the body, of course, can change. Thus, it is desirable to consider the ship hull's rigid body motions over geometric constraints. Therefore, the algorithm investigated in [5] is applied to the dynamic rigid body motion constraints.

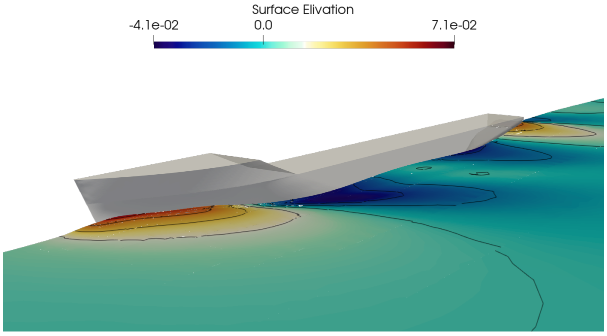

Figure 1: *Initial setting of a MOERI Container Ship (KCS) at smooth water conditions with elevation of the free surface.*

Moreover, the rigorous handling of the turbulence model is an open subject in computational fluid dynamic shape optimization with high Reynolds number flow. For the sake of simplicity the corresponding adjoint equations of the turbulence model, used to determine the fluid dynamic state variables, often is neglected (frozen turbulence assumption). Beside the PDEs which need to be implemented the choice of the correct boundary conditions for high Reynolds number flows is not trivial. Usually the high Reynolds number boundary conditions are based on the logarithmic law of the wall. A corresponding adjoint could be derived within this project [6]. In this project the adjoint turbulence equations are implemented within the framework FreSCo^{+} and the influence on the shape optimization procedure and the final shape is subject to ongoing investigation.

WWW

`https://www.c3s.uni-hamburg.de/rtg2583/research/research-area-o.html`

More Information

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