Fluid Dynamic Options for Reducing CO_2 Emissions

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Abstract

The paper surveys hydrodynamic options to reduce emissions by making ships more fuel efficient. The discussion covers modern techniques for hull and appendages design and trim optimization in operation. The approach for formal lines optimization is described, including parametric hull modelling, computational fluid dynamics, and optimization and stability analyses for constraints. Presently used numerical tools are described, as well as frontier applications using more comprehensive flow models with larger computational requirements. Design aspects and tools for modern design of appendages, including propellers and rudders, are briefly discussed. Trim optimization is applied to ships in service. The underlying approach is explained and an onboard tool described. Case studies from industry are used for illustration.

1. Introduction

Ship propulsion is responsible for the largest part of ship emissions for virtually all ships. Subsequently efforts to reduce emissions frequently focus on reduction of the required ship propulsion power. Surveys on partial aspects of fuel saving options have been published before. Several HSVA (Hamburg Ship Model Basin) publications, *Hollenbach et al. (2007), Hollenbach and Friesch (2007), Mewis and Hollenbach (2007),* have given rather comprehensive overviews of hydrodynamic options in design and operation of ships. *Bertram et al. (2009)* give a holistic cursory overview of options to reduce emissions, covering hydrodynamics, machinery and operation. Therefore we focus here on developments of the more recent years, describing in particular the role of modern simulation techniques in exploiting dormant saving potential in more detail.

2. Propulsion Power – Components and Options

We still use traditional hydrodynamic approaches to decompose the power requirements into resistance and propulsion aspects. While propeller and ship hull should be regarded as systems, decomposing helps to bring structure analyses and makes the task to find more fuel efficient ships more manageable in practice.

There are many ways to reduce the resistance of a ship. On the most global level, there are two (almost trivial) options:

- *Reduce ship size:* At first glance, it is trivial: Smaller ships consume less fuel. But the potential for weight reduction is rarely used to its full extent. In a recent application, the initial steel weight was reduced by more than 2% checking first scantlings with POSEIDON (Germanischer Lloyd's software for 3d ship structural modeling) and then verifying critical spots by finite element analyses (FEA). The savings in steel cost alone justified the expense for the analysis for a single ship. The savings are much larger when considering series of ships and the accumulated fuel savings (which are approximately proportional to the total weight of the ship). In addition, reducing the required power during the design stage by the assorted measures as discussed below will reduce in turn the weight of engines, power trains and fuel tanks and yield considerable secondary savings due to smaller ship size.

- *Reduce speed:* Speed reduction is a very effective way to reduce fuel consumption and emission. Slow steaming reduces fuel consumption significantly. However, the ship is then operated in off-design, thus sub-optimal conditions. It is far more effective and economical to design ships in the first place for lower speeds. Margins for rare high-speed operation are expensive and may be better covered by falling back on the auxiliary engine power (power take-in (PTI) via shaft generator).

The largest levers in ship design lie in the proper selection of main dimensions and the ship lines. Experts like ship model basins or ship efficiency consultants can assess the impact of main dimensions based on their experience and data bases. On a more detailed level, for a given speed and ship weight, all components of the ship resistance may offer fuel saving potential. The contribution of the resistance individual components to the total resistance depends largely on ship speed and ship size, as exemplified in Table I. Here the non-dimensional speed parameter Froude number is used: $F_n = V / \sqrt{gL}$. V is the ship speed in m/s (1 kn = 0.5144 m/s), g = 9.81 m/s^2 and L is the ship length between perpendiculars.

Table I: Distribution of resistance components for smooth-hull ship

	F_n	friction	wave	residual
Tanker 250000 tdw	0.131	66%	8%	26%
Bulker 170000 tdw	0.145	66%	10%	24%
Bulker 45000 tdw	0.171	65%	10%	25%
Tanker 41000 tdw	0.181	65%	10%	25%
Container 10000 TEU	0.234	63%	25%	12%
Container 3500 TEU	0.250	60%	30%	10%
Catamaran ferry	0.700	30%	60%	10%

The magnitude of a resistance component is an important aspect in focusing the attention in the quest to improve fuel efficiency. Another important aspect is the degree to what the resistance component can be influenced in design or operation. This will be briefly discussed in the following for each resistance component, including now also additional resistance components:

- *Frictional resistance of bare hull:* The frictional resistance for given speed depends mainly on the wetted surface and the surface roughness of the hull. For given main dimensions and form parameters, there is little variation in wetted surface and hence little room for improvement. The surface roughness is influenced by the choice of coating and appropriate antifouling management over the life-time of the ship. For new coatings, an average hull roughness of 65 μm is very good, 150 μm standard, and > 200 μm sub-standard. As a rule of thumb, every 25 μm of hull roughness corresponds to 0.7-1% of propulsion power, *N.N. (2008).*

- *Wave resistance of bare hull*: Wave resistance offers large design potential. Moderate changes in lines can result in considerable changes of wave resistance. However, a bulbous bow changes effectiveness with speed. Ideally bulbous bows should be designed for a speed profile, not just for a single design speed that is in reality rarely used. Modern design practice employs CFD (computational fluid dynamics) to derive ship hull forms with low wave resistance, Fig.1, *Bertram (2000).* Because of the importance of this resistance component, the procedures are discussed in more detail in a dedicated chapter.

- *Residual resistance of bare hull*: Flow separation occurs when the velocity gradients become too large in a flow. Large curvature in flow direction should then be avoided. Flow separation in the aftbody is delayed by the flow acceleration due to the propeller and different in model scale and full scale. CFD simulations may help in finding suitable compromises between hydrodynamic and other design aspects. Local hull modifications, often counter-intuitive to traditional design experience, have been proven to increase fuel efficiency further for given payload, Fig.2, *Harries et al. (2007).*

- *Resistance of appendages*: Appendages contribute disproportionately to the resistance of a ship. CFD simulations can determine proper alignment of appendages and design of high-performance rudders, Fig.3. Rudders offer an often underestimated potential for fuel savings. Compared to a conventional semi-balanced rudder, a twisted rudder with Costa bulb may have 4% lower power consumption, *Hollenbach and Friesch (2007).*

- *Added resistance due to seaway:* Frequent industry practice adds 15% as “sea margin”. However, sea margins in design should be adapted to ship type, ship size and intended operational trade. Over-sized engines translate into significant waste of fuel over the life-cycle of a ship.

- *Added resistance due to wind*: Air resistance contributes typically 2-4% to the overall resistance. For most cargo ships, wind resistance may be improved by up to 20% maximum, reducing the global impact on fuel savings to less than 0.5%.

For each draft and speed, there is a fuel-optimum trim. For ships with large transom sterns and bulbous bows, the power requirements for the best and worst trim may differ by more than 10%, *Mewis and Hollenbach (2007).* Decision support systems for fuel-optimum trim have been proven to result in considerable fuel savings for relatively low investment, *Hansen and Freund (2010).* They are expected to become a standard feature on larger cargo ships within the next decade. They will be discussed in more detail in a dedicated chapter below.

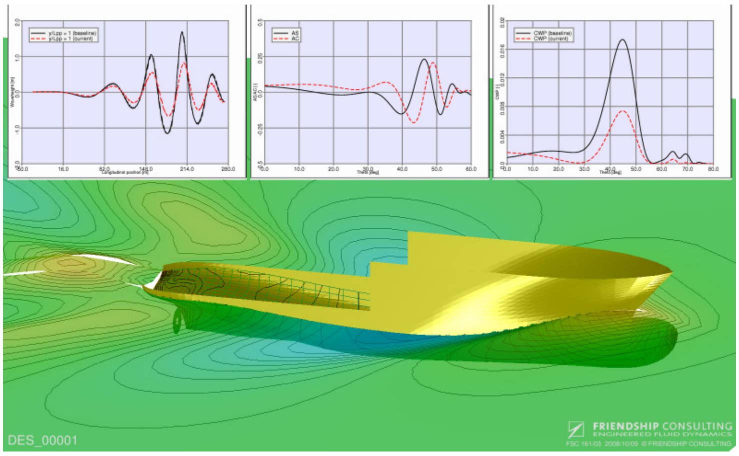


Fig.1: Hull lines optimization for offshore tug

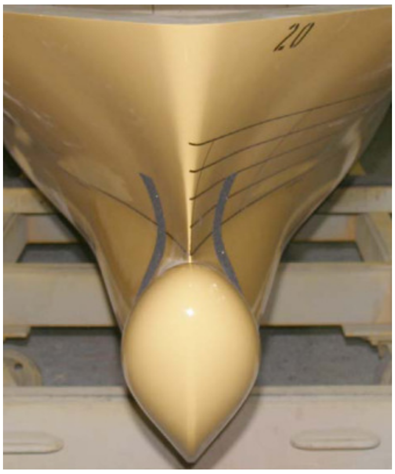


Fig.2: Local hull modification found by CFD, verified by model test, photo courtesy of HSVA

The propeller transforms the power delivered from the main engine via the shaft into a thrust power to propel the ship. Typically, only 2/3 of the delivered power is converted into thrust power. Various propulsion improving devices have been proposed over the decades, *Bertram et al. (2009),* often with questionable claims concerning their associated fuel savings. It is highly recommended to use modern CFD methods, namely so-called RANSE solvers, to assess the effectiveness of such devices at full scale conditions. The same CFD methods are used to aid the design of hull, propeller and appendages in terms of hydrodynamic interaction, Fig.4.

Ships are frequently tuned for a design speed, but later operated most of the time at lower speeds, even when they are not “slow-steaming”. If designed for a more realistic mix of operational speeds, ships are estimated to exploit further fuel saving potential. Similarly, an even speed profile in operation saves fuel. This is largely a question of awareness. Fuel monitoring systems have proven to be effective in instigating more balanced ship operation with fuel (and emission) savings of up to 20% in the electrical onboard energy, translating into 2% of the total fuel consumption for typical cargoships.

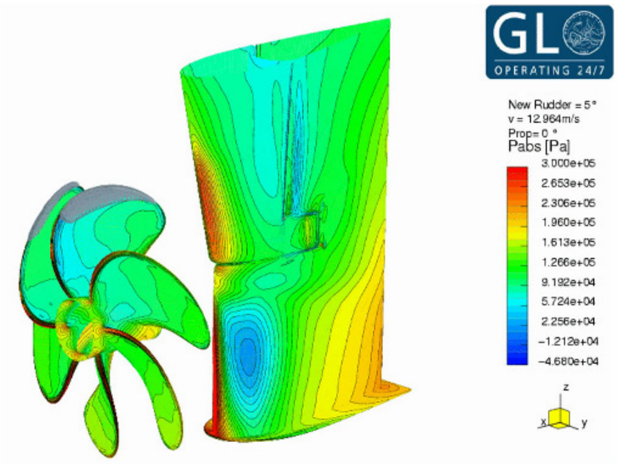


Fig.3: CFD for low-cavitation, high-efficiency rudder

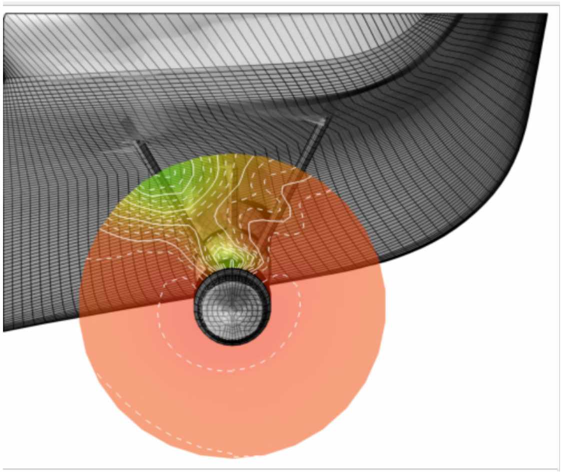


Fig.4: CFD for wake and propulsion improvement, www.friendship-system.de

3. Hull Lines Optimization

For a formal ship hull optimization, the complete process of generating the hull shape, executing the flow analysis, and assessing the objective function must be defined fully automatically. This allows executing the process in a highly parallelized manner on a modern high performance cluster, controlled by a suitable optimization toolkit. Examples for such automated ship hull optimization for various ship types can be found in *Dudson and Harries (2005), Hutchison and Hochkirch (2007), Harries et al. (2007), Bertram and Hochkirch (2009), Oossanen et al. (2009).* The approach is applicable for a wide range of ships, from slow tankers to fast semi-displacement yachts.

The potential for improvement varies, depending on the share of the wave resistance on the total resistance and on how much effort was already spent on the hull design. For example, a formal optimization may offer 1-2% improvement for containership hulls that are deemed already ‘optimized’ in limited form variations with CFD and model tests in model basins. For fast ships (for example fishing vessels, megayachts, ferries) the potential is larger as the wave resistance accounts for a larger percentage of the total resistance. For an offshore supply vessel, savings of 16% were obtained in one case. The range may thus be given as 1-16%, with 4-5% as typical values. See *Bertram and Hochkirch (2009)* for a more detailed description of how our hull optimization framework combines parametric geometry modeling, potential free-surface flow simulation, hydrostatic analyses, and multi-criteria optimization.

The state of the art in designing fuel efficient ships in the 1990s was a combination of limited form variations (typically 5 to 20) analysed by potential flow codes that neglected friction and breaking waves. The technology progressed in the subsequent decade to formal optimization using still potential flow codes. In such a formal optimization, typically 5000 to 20000 design alternatives were evaluated. We are active in research to push the frontier further and exploit the remaining potential for improving fuel efficiency of ships. The state of the art for the coming decade will be formal optimization based on CFD codes that include breaking waves and viscosity, allowing also high-fidelity assessment of the flow in the aft region of ships. First pilot applications have been performed, coupling our usual framework with the CFD solver OpenFOAM.

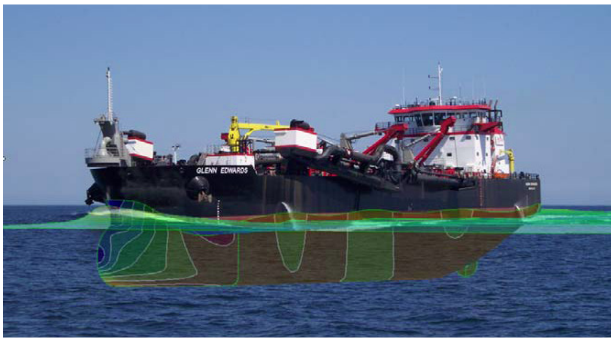


Fig.5: Hull optimization for a dredger

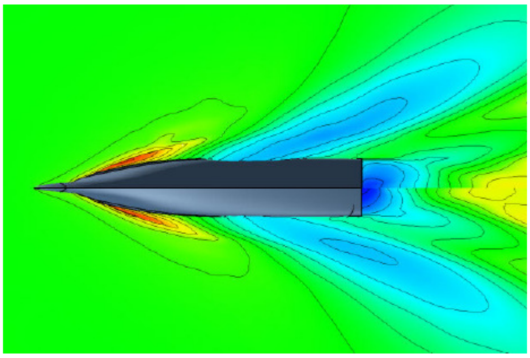
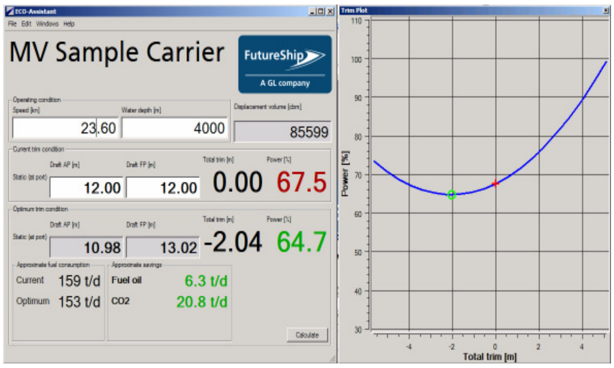


Fig.6: Hull optimization for fast megayacht

4. Trim Optimization

The trim of a ship influences significantly the fuel consumption of a ship. Unfortunately, the fuel optimum trim of a ship depends on the displacement and speed of a ship, as well as the water depth on shallow water. Therefore, no simple rule of thumb can be given for the optimum trim. While trim-power tables based on model tests are sometimes available on board, crews generally shy away from the cumbersome task of using them. FutureShip now offers a service, where a comprehensive hydrodynamic knowledge base for a specific ship is created based on numerical propulsion tests with an extensively validated CFD method, *Hansen and Freund (2010)*. Often more than 1000 different operational conditions are investigated for this purpose. This knowledge base is then combined with a very simple user interface in the ECO Assistant software, Fig.7, which can be installed on board or on shore. The crew then inputs just a few simple parameter (displacement, intended average speed, average water depth) and immediately gets the most fuel efficient trim displayed, along with the savings in fuel versus the even keel condition. In the few cases, where this optimum trim cannot be achieved due to ballast or other constraints, the ECO Assistant allows the crew to determine the best feasible trim and quantifies the associated savings. Savings of up to 5% compared to traditional even-keel trimming are not uncommon, Fig.8. While the tool is intended to support fleet in service, it may already be applied in newbuilding projects and given to the ship operators for added value.



MV Sample Carrier

Operating condition
Speed [kn] 23.60
Water depth [m] 4000
Displacement volume [cbm] 85599

Current trim condition
Static (at port) Draft AP [m] 12.00 Draft FP [m] 12.00 Total trim [m] 0.00 Power [%] 67.5

Optimum trim condition
Static (at port) Draft AP [m] 10.98 Draft FP [m] 13.02 Total trim [m] -2.04 Power [%] 64.7

Approximate fuel consumption
Current 159 t/d
Optimum 153 t/d

Approximate savings
Fuel oil 6.3 t/d
CO2 20.8 t/d

Fig.7: User interface for trim assistant software

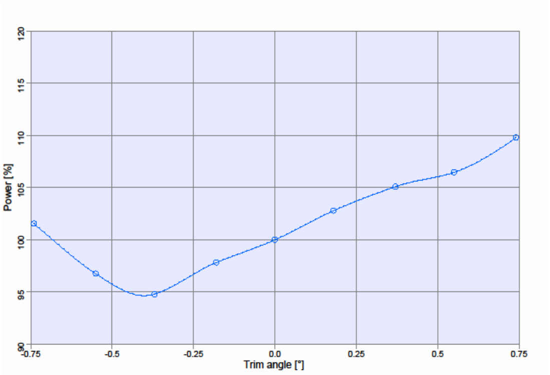


Fig.8: Simulation-based optimum trim (curve for one speed and one average draft) for a multi-purpose carrier

5. Conclusion

There are many hydrodynamic levers to save fuel and thus emissions for ships. Modern simulation allows exploitation of saving potential beyond the widely known traditional option. This potential is significant and dedicated consultancy companies like FutureShip can support ship owners and operators in making the most of it.

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