Slow Steaming Bulbous Bow Optimization for a Large Containership

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Formal optimization is applied to a containership. The generic case assumes an existing containership that considers slow steaming due to high fuel prices. A refit of a bulbous can be seen as a typical investment option, where potential savings have to be considered against initial investment. The potential savings are evaluated for two cases: (1) only the bulbous bow is changed (refit) and (2) the forebody of the ship can also be modified (newbuilding). The formal optimisation uses the FRIENDSHIP Framework for the parametric shape description, FS-Equilibrium for hydrostatics, FS-Flow as wave resistance flow solver for resistance evaluation and FS-Optimizer for the formal optimisation involving both deterministic and stochastic single and multi-objective algorithms. The starting geometry shows little potential for improvement at design speed, but for slow steaming 2% improvement appear feasible. Considerable improvements (near 4%) in carrying capacity at constant speed or fuel reduction are feasible if the forebody can be modified. If the bulbous bow is modified during a regular docking period the investment is estimated to have payback in less than 2 years.

1. Introduction

Fuel prices escalated to more than 700 $/t heavy fuel oil (HFO) in 2008 to roughly three times of the rather low levels of the 1990s. In addition, increasing public awareness and political pressure started restrictive legislation aimed at curbing emissions, particularly CO_2 emissions. IMO (International Maritime Organization) is expected to pass regulations on CO_2 (carbon-dioxide) ship emissions after 2012, adding pressure to reduce fuel consumptions. The world financial crisis in fall 2008 temporarily induced a drastic decline of oil and fuel prices (from 700 $/t in August 2008 to 350 $/t HFO in October 2008), but long-term predictions assume fuel prices including CO_2 emission charges between 500 and 1000 $/t HFO for ship owners.

There are many levers to reduce ship fuel consumption (and thus emissions), *Bertram et al. (2009).* One of the most attractive levers is optimizing the lines of a ship, particularly the bulbous bow. This is very attractive in the design stage, but refit options may be still attractive enough to be considered, particularly when the ship is operated at a much slower speed than it was originally designed for. Such “slow steaming” at e.g. 70% of the design speed was a frequent reaction of containership operators to the high fuel prices. Ship, engine and propeller are then operated in off-design conditions opening opportunities for new optimisation for the lower speed.

2. Relevant previous work

2.1. Parametric ship design

Parametric ship design hull has been as a powerful modelling technique during the last decade. Instead of describing the hull shape’s properties by a large network of lines and points requiring a lot of manual work, the parametric modelling approach employs so-called high-level form descriptors which describe characteristic properties, e.g. of the sections by means of longitudinal distributions. Our preferred technique builds B-spline curves from selected properties. These can be described directly, differentially or even by integral formulations. The vertices of the final spline are then automatically placed to ensure a fair distribution of the property required. A typical example is the sectional area curve of a hull where the integral value reflects the required buoyancy. Direct parameters are derived from the main section geometry and a differential parameter (zero slope) is required at the main section location. The generation of such ‘meta curves’ is set up in a way that additional constraints may be added later while missing information is found automatically by an internal optimization focusing on maximum fairness, *Harries (1999).*

Besides fully parametrically described (FPD) hulls, a complementary technique – partial parametric modelling (PPM) – has been developed which directly works on a baseline design and allows more efficient preparation of the geometry model. Here local modifications of the baseline shape are defined by scaling, shifting and similar techniques.

2.2. Ship Hull Optimization

Based on a parametrically modelled geometry, an automated optimization task can conveniently be set up. The parameters are considered as free variables and a suitable objective function is selected. Typically, the objective function is the resistance or nominal thrust at a design service speed. However, given the nature of the specific project, different objective functions may be taken into account, e.g. performance at more than one condition.

For a most efficient use of this technique the whole process of generating the hull shape, execution of the analysis and assessment of the objective function needs to be defined completely automatically, thus allowing the process to be performed in a highly parallelized manner on a modern high performance cluster, controlled by a suitable optimization toolkit. For examples of successful application of this technique please refer to *Dudson and Harries (2005), Hutchison and Hochkirch (2007), Harries et al. (2007).*

3. Framework & Tools

Today several tools are available for addressing the single task required for such an optimization. However, as the whole design loop needs to work without user interaction, the interfacing between different tools (e.g. the geometry modeller and the CFD tool) requires much care to ensure a smooth workflow. Below the tools used for the presented are discussed:

3.1. FRIENDSHIP Framework

The FRIENDSHIP-Framework is a unique Computer Aided Engineering (CAE) system, integrating geometric modelling, simulation, systematic variation, and formal optimization in the design of ships and turbo-machinery, *Abt and Harries (2007)*. Its parametrically oriented platform conveniently allows modelling complex geometries (e.g. ship hull or propeller) by a selection of high-level shape descriptors. A typical scenario is that longitudinal properties of the sections are modelled by fairness optimized B-spline curves.

3.2. FS-Equilibrium

FS-Equilibrium is a workbench for analysis of equilibrium conditions of floating bodies in six degrees of freedom. Typical applications are all types of hydrostatic analysis, manoeuvring simulation, and velocity predictions for ships and sailing yachts. Due to its modular setup, the code is easily adapted to work for a specific design problem. An application programming interface (API) is available for optional user-defined modelling of forces. For the task at hand only a small subset of the functionality was employed to monitor the changes of hydrostatic properties due to the bulb and forebody changes.

3.3. FS-Flow

For the design task at hand, the most important objective was the wave making resistance of the hull at the considered speed. Rankine panel codes considering the nonlinear free-surface boundary condition are the standard tool of choice to assess wave making and support bulbous bow design, *Bertram (2000)*. The in-house code FS-Flow has special interfaces with the other tools discussed. FS-Flow uses a panel representation of the hull (including lifting surfaces if applicable) and a portion of the free water surface. The source strength on each panel is adjusted to fulfil the various boundary conditions, namely zero normal velocity on the hull and kinematic and dynamic boundary conditions on the water surface. Lifting surfaces like keel, rudder and fins (e.g. in case of sailing yachts or stabilizer systems) are modelled in FS-Flow by lifting patches which carry in addition to the source panels also a dipole distribution, enforcing a Kutta condition at the trailing edge. The ship's dynamic floating position and the wave formation are computed iteratively. After each iteration step, the geometry of the free surface is updated and the sinkage, trim, heel and propeller thrust of the vessel are adjusted. The calculations are considered to be converged when all forces and moments are in balance and all boundary conditions are fulfilled. Having determined the source strengths, the pressure and velocity at each point of the flow field can be calculated. The wave resistance can be either computed by integrating the pressure over wetted surface of the hull or from wave cut analysis, *Heimann et al. (2008)*.

The employed approach is based on potential flow theory. Therefore viscous effects such as a recirculation zone at the stern cannot be modelled correctly. However, in hull optimization studies, the focus is often on the forebody where potential flow approximates the real conditions well, unless major wave breaking occurs. Generally, at higher speeds the bow and stern wave pattern strongly interact and the whole ship wave pattern is needed to get the correct picture. If in an optimization study the stern shape is left unchanged then the effects of forebody hull variations on the wave generation can be traced with reasonable accuracy even though the quality of the stern wave prediction must be judged with caution. The total resistance is predicted on the basis of the non-viscous resistance components from the CFD simulation and an estimate of the viscous components either by the ITTC method, e.g. *Bertram (2000)*, which may optionally be based on local flow properties, or by an accompanying boundary layer computation. While the integral resistance values are only indicative, it is commonly agreed that design rankings are correct with good accuracy if design modifications are limited to the forward half of the ship. This has been confirmed in numerous optimization projects.

3.4. FS-Optimizer

Optimization involves varying parameters to improve objectives while keeping given constraints. In ship design, candidate solutions must be created (typically by CAD systems) and objective function(s) and constraints may involve assorted software tools. The accuracy of these tools drives to a large extent the quality of the results.

FS-Optimizer is a generic optimization toolkit for simple set-up of tailored applications, combining a selection of arbitrary analysis programs (needed for objective functions and constraints), applying a variety of methods for designs space exploration and formal optimization. Constraints can be included and monitored during the optimization. The program has a graphical interface and can also be run in batch mode for time consuming numerical computations on main frame computers. The program can run in unlimited threading mode to make full use of parallel computing environments like HPC (high performance computing) clusters. Advanced users may incorporate own algorithms to control the optimization while still taking advantage of the file and directory handling provided by FS-Optimizer.

4. Application

4.1. Test case

Based on its extensive experience for containerships, Germanischer Lloyd created the test case GENCON (generic containership), Fig.1, Table I. While not actually built, the hull is representative for a typical large containership used between Europe and the Far East, featuring relatively high speed, slender lines with large transom stern and large flare. Similar ships were built in large series in the past decade, when the fuel prices were still very low compared to the present level. Several ship owners reacted to the drastic rise in fuel prices by "slow steaming", reducing typical design speeds of 25 knots to typical operating speed of 18 knots.

The bulbous bow represents a state-of-the-art shape obtained by conventional simulation-based design. This approach involves typically the evaluation of 5 to 10 variants only. Experienced experts may study flow details of base design to derive recommendation of how to change the design to create new candidate solutions. It is thus rather an expert guided search, but the approach has been often described (erroneously) as optimisation.

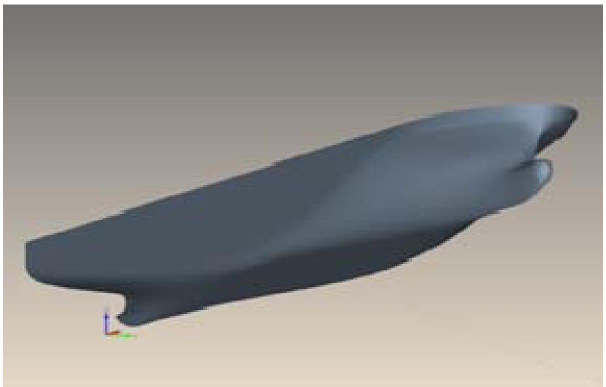


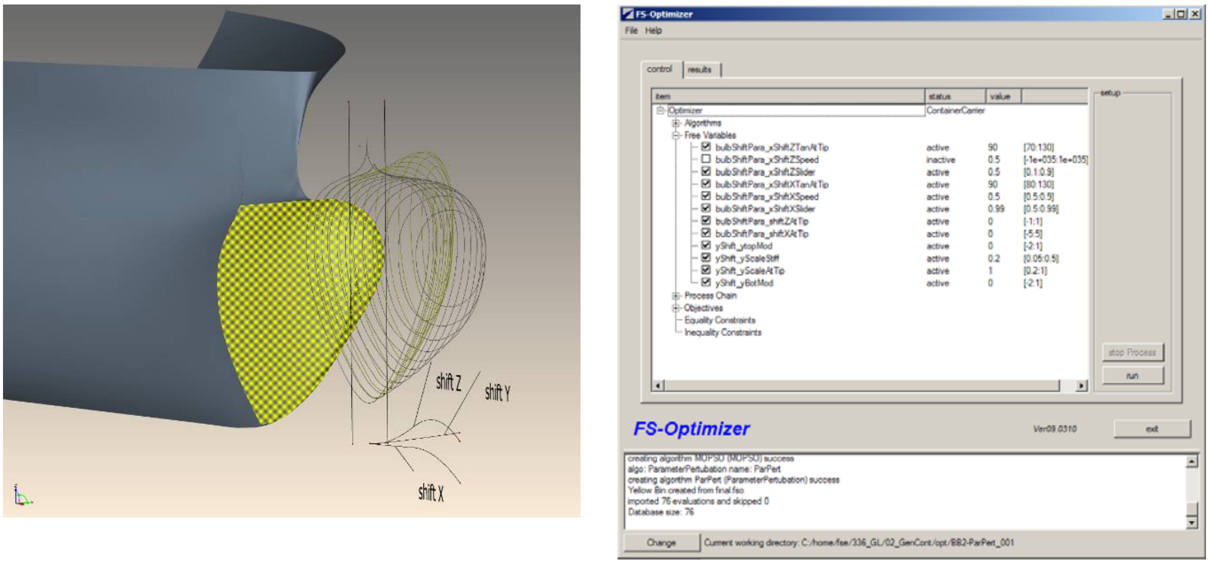
Fig.1: GENCON geometry

Table I: Main dimensions

Length L_{pp}	320.00 m
Width B_{max}	42.80 m
Draft T	13.50 m
Displacement	118000 t
Design speed V_d	25 kn
Operating speed V_s	18 kn

4.2. Parametric model

The idea of this project was to investigate the potential savings by refitting a bulbous bow. Therefore the parametric model for this task was focused on the bulbous bow region only and maintained the section shape at the forward perpendicular. In addition, a tangency condition was maintained between the forebody and the bulbous bow. Although in principle possible, maintaining curvature continuity (at the transition between forebody and bulbous bow) was not considered as important for this study.



item	status	value	
Optimizer	ContainerCarrier		
Algorithms			
Free Variables			
☑ bulbShiftPara_xShiftZTanAtTip	active	90	[70:130]
☐ bulbShiftPara_xShiftZSpeed	inactive	0.5	[-1e+035:1e+035]
☑ bulbShiftPara_xShiftZSlider	active	0.5	[0.1:0.9]
☑ bulbShiftPara_xShiftXTanAtTip	active	90	[80:130]
☑ bulbShiftPara_xShiftXSpeed	active	0.5	[0.5:0.9]
☑ bulbShiftPara_xShiftXSlider	active	0.99	[0.5:0.99]
☑ bulbShiftPara_shiftZAtTip	active	0	[-1:1]
☑ bulbShiftPara_shiftXAtTip	active	0	[-5:5]
☑ yShift_ytopMod	active	0	[-2:1]
☑ yShift_yScaleStiff	active	0.2	[0.05:0.5]
☑ yShift_yScaleAtTip	active	1	[0.2:1]
☑ yShift_yBotMod	active	0	[-2:1]
Process Chain			
Objectives			
Equality Constraints			
Inequality Constraints			

```
creating algorithm MOPSO (MOPSO) success
algo: ParameterPertubation name: ParPert
creating algorithm ParPert (ParameterPertubation) success
Yellow Bin created from final.fso
imported 76 evaluations and skipped 0
Database size: 76
```

Current working directory: C:/home/fse/336_GL/02_GenCont/opt/BB2-ParPert_001

Fig.2: Parametric shift functions for modification of the baseline bulb geometry and optimization setup within the FS-Optimizer

Instead of implementing a completely new geometry for the exemplary state of this study a partial parametric model was implemented. Such models rely on a baseline geometry definition which is modified by means of various shift and scaling functions, Fig.2. Table II lists in more detail the variations which where available for the optimizer to vary. Altogether this added up to 11 free variables defining the available shape variations.

As an alternative approach, as redesign option, a fully parametric model of the whole forebody was employed. This model features some 100 design parameters of which about 40 where selected as free variables for a more rigorous approach; details of this model shall be omitted for this paper.

Table II: Parametric bulb modifiers

xShiftZ	a vertical shift of the bulb sections to allow the bulbous bow tip to be lowered or raised with respect to the baseline bulb. As the bulb geometry at the FP could not be changed this shift was fading out when approaching the FP. The displacement at the tip, the initial change rate as well as the as the grade of decrease where used as free variables.
xShiftX	A longitudinal shift of the bulb sections to allow elongation or shortening of the bulbous bow. Similar parameters as for the vertical shift have been made available to the optimizer.
yModifier	In order to allow for changes in beam a scaling function has been used which, again, gradually decreases when approaching the forward perpendicular to match the unaltered hull shape. Further a vertical variation of this scaling was implemented to allow for vertical shifts of the displacement distribution

4.3. Optimization of bulbous bow only (refit option)

For the design task at hand an initial design space exploration was undertaken where the design space was sampled by a low discrepancy sequence to subsequently increase the density of samples while avoiding gridlines and clustering. We usually apply a Sobol algorithm for this task. Utilizing the full power of a 512 node HPC cluster, some 20000 designs were created and analyzed for the discussed study. Based on the results of the exploration study a selection of favourite shapes was identified and used as starting points for subsequent deterministic optimization.

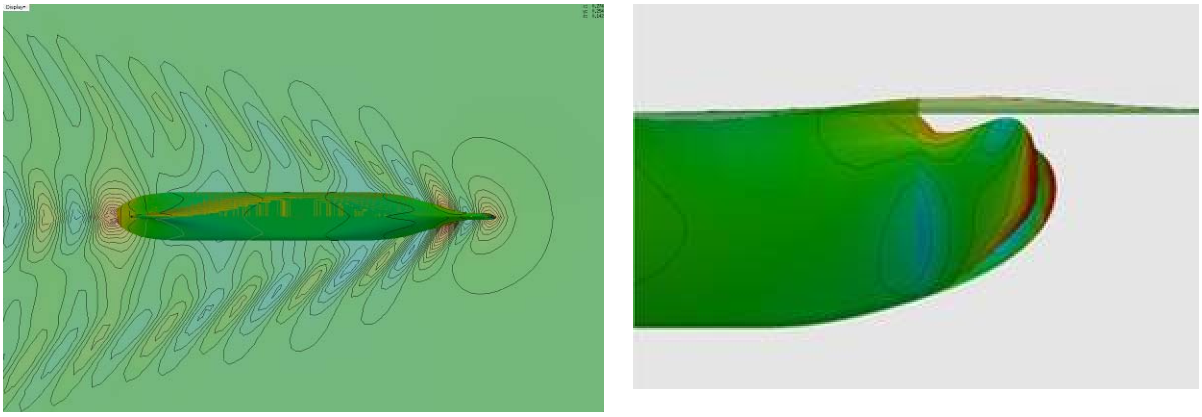


Fig.3 Original and modified bow in flow analysis; global wave pattern with original hull on lower half and optimised hull on top half (left) and bow detail (right)

Fig.4 depicts a pareto plot giving the performance of the bulbous bow variations at the two operating conditions selected for this study. The blue circle denotes the baseline design, while the green circle and green triangle point out two selected candidates. There is generally a very strong relation for the performance at these two speeds. However, there are a significant number of designs which seem to outperform the baseline design in both cases. A gain of more than 2% seems feasible for the slow steaming speed, and even more than 1% seem feasible for improvement on the design speed. Not surprisingly, the potential for improvement at the slow speed is higher than for the design speed, as this scenario was probably not considered at all when the initial design was studied.

Fig.5 shows the trade-off between displacement and resistance. The baseline design is marked again using the blue circle. The plot shows that generally bulbs with lower displacement are more favourable for the slow steaming speed, i.e. a similar impact on the wave pattern can be achieved by a smaller bulb which has also less frictional drag.

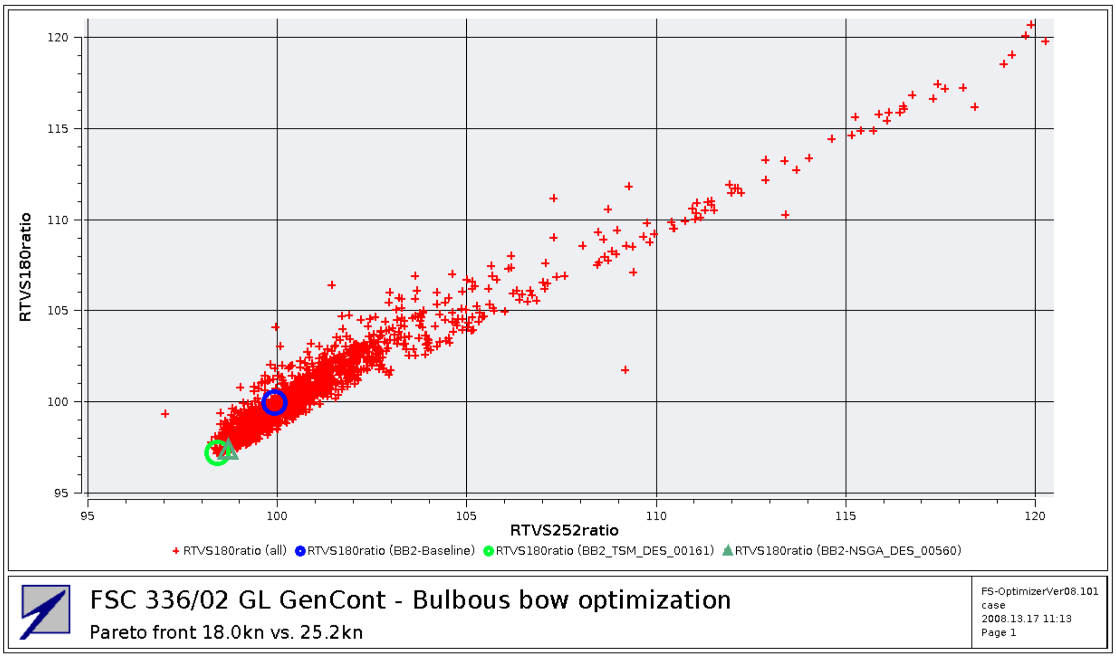


Fig.4: Performance of design variations on 18kn and 25.2 kn

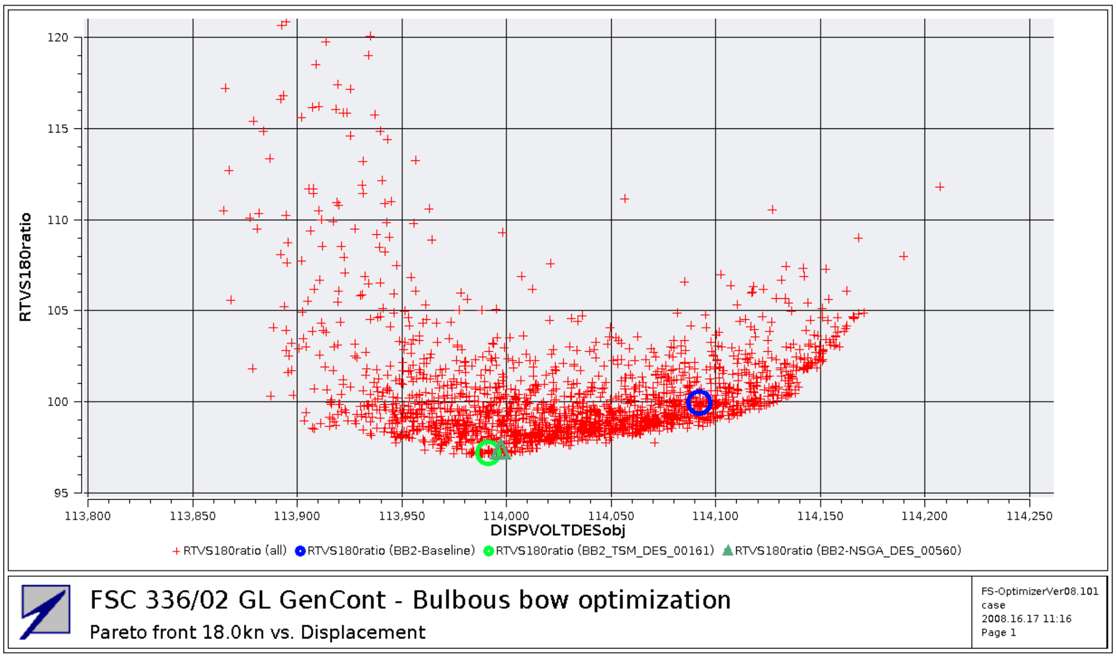


Fig.5: Trade-off between displacement changes of the bulbous bow and the resistance

Fig.6 shows a history plot when using a deterministic search strategy to find the optimum bow configuration. The deterministic approach is less costly in terms of resources; however, since the evaluations must be performed sequentially, the overall turnaround time may be larger. Furthermore, a deterministic approach will usually be limited to find a local minimum, while the design space (especially for large sets of free variables) is very likely to be multimodal. Thus, an initial design space exploration is generally recommended.

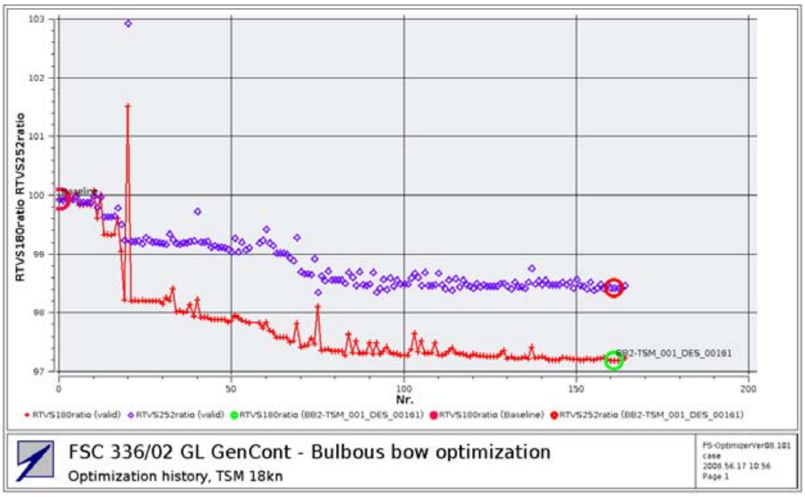


Fig.6: Optimization history of a deterministic strategy

4.4. Optimization of forebody (redesign option)

To obtain some feeling for the overall potential for improvement of the lines, the optimization strategy discussed above was applied to a parametric model of the whole forebody. This approach is not feasible for a refit. But it is interesting to see the potential for a new design.

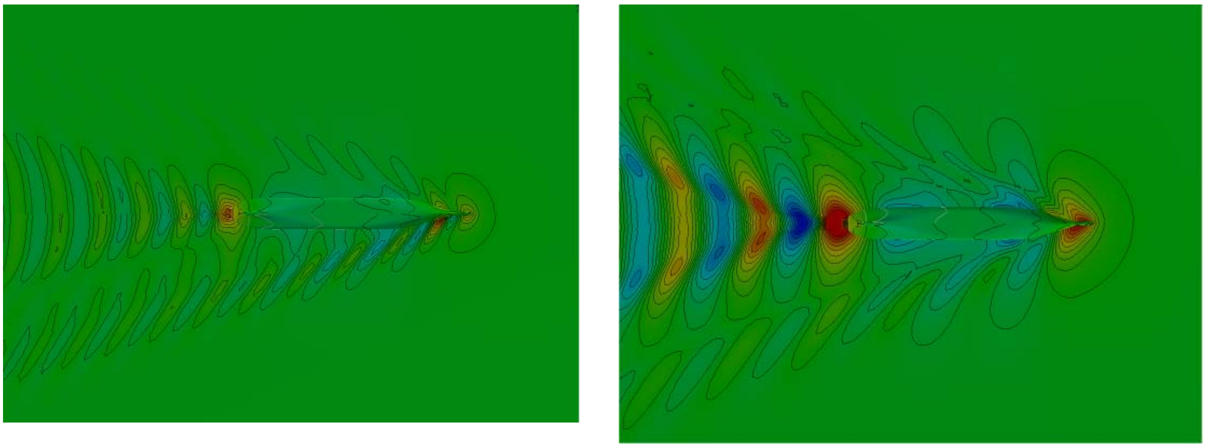


Fig.7: Wave pattern for base design (lower half) and optimized design (upper half) for 18 knots (left) and 25 knots (right)

Fig.8 shows the corresponding pareto plot for the exploration series which included shape variations to the full forebody: Small dots denote all designs created; the slightly larger green diamonds indicate which designs could conform the required design constraints. Here hydrostatic stability and displacement volume were constrained to be at least as high as in the base design.

As expected, a significant larger variation in performance is possible. Considering the performance at the two speeds as objective functions, the dashed line sketches the pareto front. This immediately highlights the importance to consider a wider selection of speeds in the design process, as the best performing design on the slow steaming speed is very bad at the higher speed. In the upper left corner valid and very good designs for the design speed can be found which perform poorly for slow speeds. The current design can be significantly improved for both speeds when working on the full forebody.

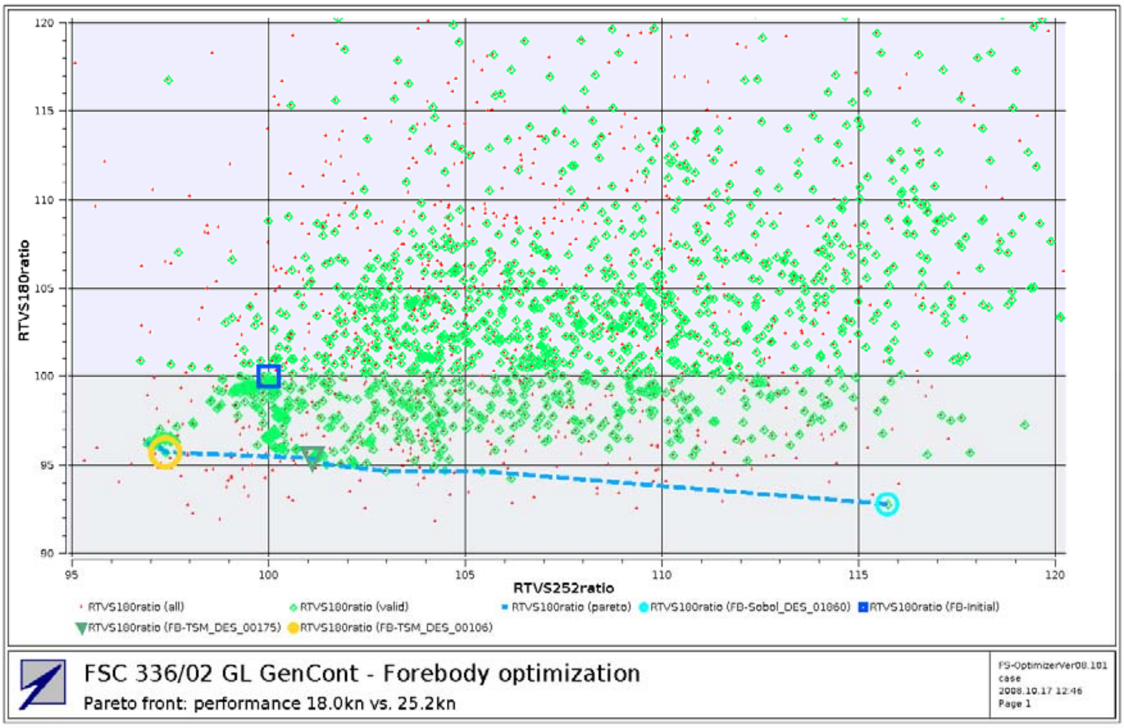


Fig.8: Pareto plot for a full forebody modification

5. Economic evaluation of refit option

We assumed the following basic data for an economic evaluation of a refit, based on interviews with ship operators and repair shipyards:

- 300 days at sea per year; the residual time is spent in port or in maintenance/repair docks
- 350 $/t heavy fuel oil; in 2008, prices dropped within a month from 600 $/t to 350 $/t; prices are expected to rise again by mid-2009.
- Conversion cost of 350000 € (corresponding to $ 450000) including the fees for determining such an optimal hull and verifying the result in a model basin, excluding opportunity cost due to dock time. The assumption is that the conversion is made during a regular dock stay which is scheduled typically every 5 years for major inspection and repairs.
- 0.177 kg/kWh specific fuel consumption of the engine in slow steaming. This value was chosen based on manufacturer specifications and measurements for similar containerships.
- 40% engine power used in slow steaming
- 2.5% obtained fuel savings by refit of bulbous bow
- Payback time calculated without consideration of interest rates; attractive payback times are so short that the error in neglecting normal interest rates is small compared to the uncertainty margins in the other assumptions.

The yearly fuel cost for the main engine amounts then to roughly $ 12 million. This leads to a payback time of 1.5 years. The fuel price of August 2008 (600 $/t) would lead correspondingly to a payback time of 10 months. Savings of only 1.5% due to a bulbous bow refit (e.g. due a larger constraints on the bow shape and pessimistic assumption for the numerical error in the procedure) and fuel price of 350 $/t would lead to 2.5 years payback time. The refit option appears thus attractive enough to be seriously considered for large containerships.

6. Conclusion

Parametric design optimization is a good tool for hull shape optimization. All relevant operating conditions should be considered in the design loop to ensure a robust design. Although the hull considered in this study was already very good for the design sailing condition, significant improvements (4-5%) were found when considering a full forebody modification (redesign option).

For the refit option (with very restricted hull modifications), significantly improved hulls for slower speed were found. These designs slightly outperform the base configuration at design speed and can thus be recommended as refit option without spoiling the design performance.

Even at currently low fuel prices, global optimization appears attractive and will become even more so as fuel prices increase.

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References

ABT, C.; HARRIES, S. (2007), *A new approach to integration of CAD and CFD for naval architects*, 6th COMPIT, Cortona, pp.467-479.
http://www.ssi.tu-harburg.de/doc/webseiten_dokumente/compit/dokumente/compit2007_cortona.pdf

BERTRAM, V. (2000), *Practical Ship Hydrodynamics*, Butterworth & Heinemann

BERTRAM, V.; FACH, K.; SAMES, P.; HÖPPNER, V. (2009), *Engineering options to reduce emissions*, 10th Int. Marine Design Conf. (IMDC), Trondheim

DUDSON, E.; HARRIES, S. (2005), *Hydrodynamic fine-tuning of a pentamaran for high-speed sea transportation services*, Int. Conf. Fast Sea Transportation (FAST), St. Petersburg
http://www.fsopt.com/downloads/2005_PaperDudsonHarriesFinal.pdf

HARRIES, S. (1999), *Parametric design and hydrodynamic optimization of ship hull forms*, Mensch & Buch Verlag, Berlin.

HARRIES, S.; HINRICHSEN, H.; HOCHKIRCH, K. (2007), *Development and application of a new Form Feature to enhance the Transport Efficiency of Ships*, Jahrbuch der Schiffbautechnischen Gesellschaft, http://www.fsopt.com/downloads/2007_STGpaperInSAC_HaHiHo.pdf

HEIMANN, J.; HUTCHISON, B. L.; RACINE, B. J. (2008): *Application of the Free-Wave Spectrum to Minimize and Control Wake Wash*, SNAME Annual Meeting & Expo, Houston
http://www.sname.org/AM2008/papers/049.pdf

HUTCHISON, B.L.; HOCHKIRCH, K. (2007), *CFD hull form optimization of a 12,000 cu.yd. (9175 m3) dredge*, 10th Int. Symp. Practical design of Ships and Other Floating Structures (PRADS), Houston, http://www.fsopt.com/downloads/2007_Hutchison_Hochkirch_Prads07_Dredge.pdf