VI International Conference on Computational Methods in Marine Engineering
MARINE 2015
F. Salvatore, R. Broglia and R. Muscari (Eds)

OPTIMIZATION FOR SHIP HULLS – DESIGN, REFIT AND OPERATION

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Key words: Optimization, Ship Design, Energy Efficiency, Trim Optimization

Abstract. This paper gives an overview of the application of formal optimization in ship design, refit of ships and operational procedures. The application cases are taken from industrial practice and recent research projects, reflecting the state of the art and near-future trends. In design, the focus is on hull optimization, based on full-scale free-surface RANSE simulations with working propeller in calm water (“numerical sea trials”). In refits, formal optimization for bulbous bows for different operational profile (in slow-steaming and partially loaded conditions) is shown to give unexpectedly large saving potential. In operation, trim optimization and weather routing are widely used applications. Recent progress in prediction of added resistance in waves benefits both weather routing and future hull optimization under consideration of added resistance in waves.

1 INTRODUCTION - GETTING THE TERMINOLOGY STRAIGHT

The term “hull optimization” is widely used and in many cases abused. Often the term “improvement” would be more appropriate than “optimization”. Muddy terminology creates confusion. We should get our terminology straight. We distinguish then the following design approaches:

- Simulation-based design

  Simulation-based design commonly employed in industry. Typically less than 10 variants are generated and assessed by more or less sophisticated simulations. Human experts look at details of the simulation (e.g. pressure distribution in critical areas) and derive recommendations for design changes. For hydrodynamic design, CFD (Computational Fluid Dynamics) techniques are applied, [1]. This by now standard design procedure is employed by many design offices and model basins around the world, but frequently we see that significant improvement beyond this approach are possible.

- Concept exploration

  Concept exploration models (CEMs) have been proposed as an alternative to ‘automatic’ optimization, [2]. More recently, “design of experiment” (DOE) has been used as a term for the same design strategy: A large set of candidate solutions is generated by varying design variables. Each of these solutions is evaluated in key performance indicators and stored. CEMs thus generate a “map” of the unknown design space. Using suitable graphical displays, the designer gets a feeling how certain variables influence the performance of the design. The approach was deemed impractical for ship design in the 1990s due the then excessive computational requirements, [3]. However, parallel computation has changed this and concept exploration is now used in commercial projects.

- Optimization

  Optimization looks at thousands or even tens of thousands of designs and uses an optimization algorithm to find the best design. For many modern optimization problems, genetic algorithms (GAs) or related evolutionary optimization algorithm are the preferred choice these days. GAs are significantly less efficient than older gradient-based search algorithms. However, they are easily parallelized and robust in finding global optima, i.e. they do not get stuck at local optima. (Single-objective) optimization is in theory a mathematically well-posed problem. However, objective and all constraints must be expressed as mathematical functions. This is not easy in practice, [2].

- Multi-objective optimization

  Optimization for multiple objectives is strictly speaking nonsense. Mathematically you can only optimize for one objective, respectively an optimum is only defined for one objective function. In layman terms, finding the fastest (objective: speed) and cheapest (objective: price) car will result in the question: Make up your mind, what do you want? Multi-objective optimization in practice is short for a combination of concept exploration and optimization. The concept exploration helps in making up one’s mind. Then objectives may be reformulated as constraints or combined in one artificial objective function using weights for the individual objectives. The “best compromise” objective function can then be determined formally by the optimization algorithm of choice.

The borderline between concept exploration and multi-objective design becomes indistinct in practice. The process of concept optimization resembles a formal optimization. A concept design family is described through parametric variations; however, concept exploration uses typically fewer parameters and fewer candidate evaluations. The key difference is that the final design solution is selected without employing a formal optimization algorithm.

2 APPLICATIONS

2.1 Ship design & refit projects

Hull optimization has become a powerful and widely accepted tool in professional ship design, as reviewed in [4]. State-of-the-art projects employ full-scale high-fidelity CFD ("numerical propulsion tests"), [5], and consider a spectrum of operational profiles rather than a single design point, [6]. Several industry projects from recent experience shall illustrate the design practice. For descriptions of the employed software, we refer to [4]. Very early design decisions have large impact on later performance. The more freedom you have, the more you can gain from making the best choices. Often, hull optimization starts with the main dimensions and displacement largely given. Then 4-6% improvement in yearly fuel consumption is typically achieved, Fig.1. But we can do better – if we start earlier, with concept exploration.

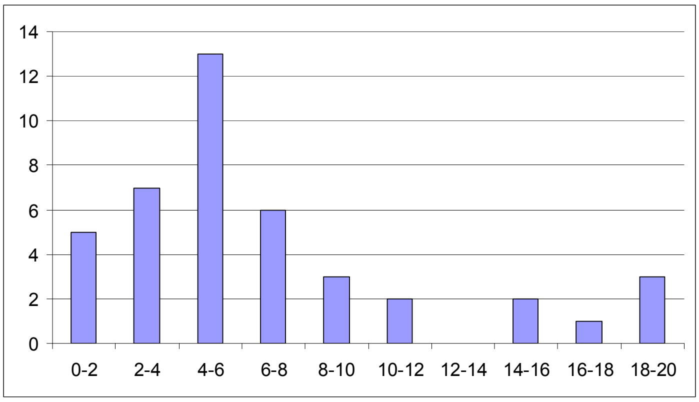

Figure 1: Gains in actual optimization projects (2012)

- Concept exploration

In a project for a fleet of containerships, a concept exploration study found the best main dimensions and key design parameters before a classical lines optimization was performed. The core objective of the study was requirements elucidation for the ship owner, exploring what may be possible when varying length, beam, block coefficient or average TEU weight. Hull shapes were generated automatically using commonly used CAD distortion techniques (Lackenby approach). The power requirements were assessed by means of a simplified numerical towing test: A fully nonlinear wave resistance code with simplified propeller model and viscous flow effects was employed. Such a tool is not sufficient for a proper numerical propulsion test, but known to give correct ranking of alternatives for similar designs and significant changes in global geometry. Correlation with in-house databases helped getting sensible correlation factors for full-scale extrapolation as needed in design. The advantage is that the tool is very fast and allows rapid design exploration, as needed in such concept exploration. Each concept resulted in main dimensions, simplified pocket plan, speed-power curve, and initial stability assessment. In total, some 8000 designs were explored. The result is "virtual map" of the design space, allowing an informed decision on the main dimensions and configuration for the intended trade mission. The logical next step after this decision was then a refinement of the design in a formal lines optimization.

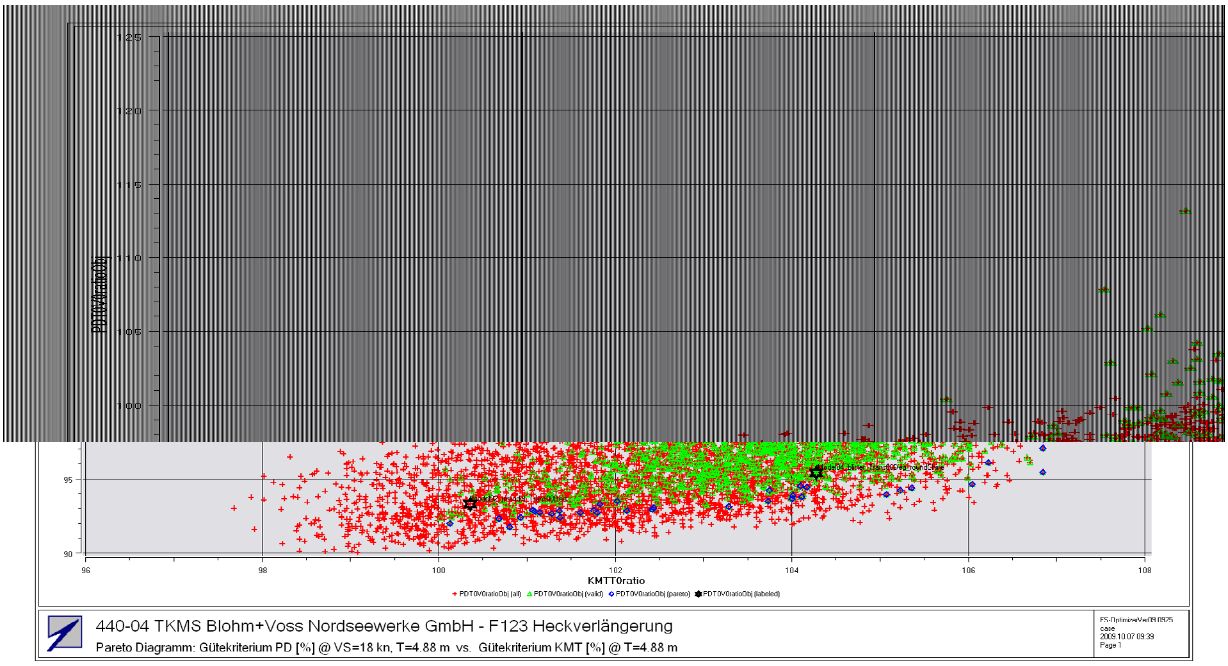

Figure 2: Pareto-diagram of required power (y-axis) and KM-values (x-axis). Each dot represents an investigated variant. Red dots violate a constraint, green dots are permissible variants.

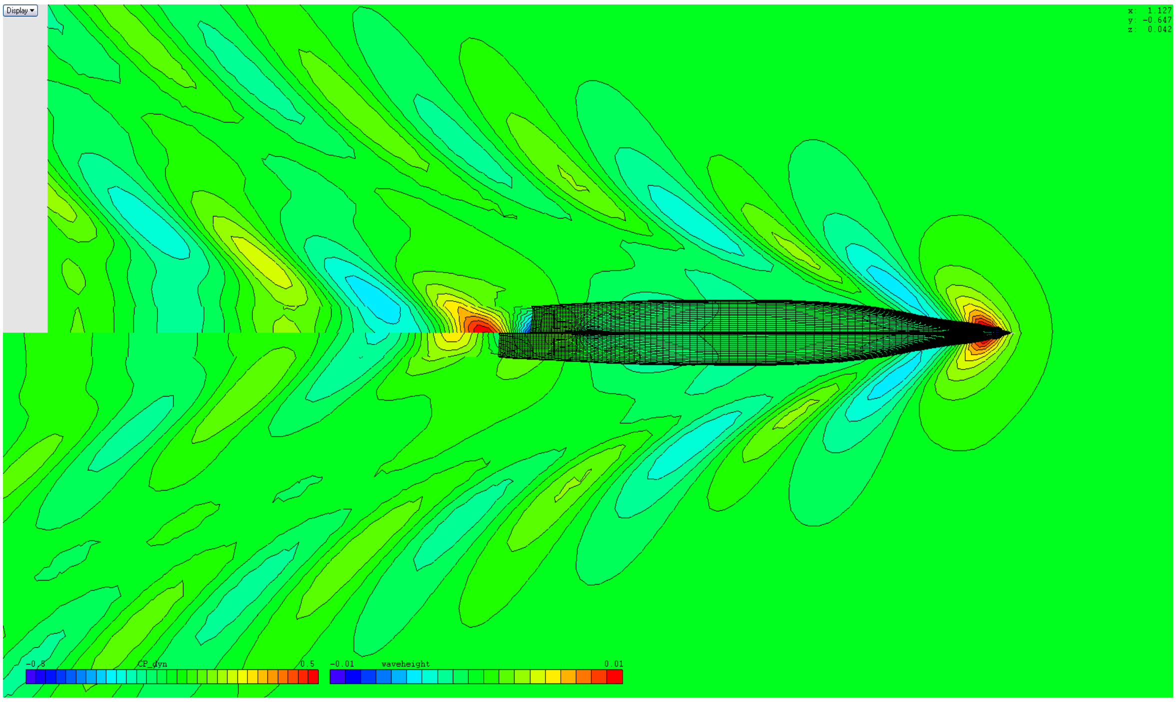

Figure 3: Wave pattern for original hull (top) and recommended extended version (bottom)

Another concept exploration study investigated an envisioned hull extension of the German Navy frigate F123. Key objectives were stability (to be increased) and power performance (to be decreased). Some 10000 variants of the new aftbody were investigated numerically, Fig.2 and Fig.3. Based on the resulting design knowledge, we recommended a detailed geometry with significantly improved stability and no hydrodynamic penalty.

- Hull optimization

A typical optimization project starts with a good design, ideally with main dimensions determined in a concept exploration study. Then the hull optimization fine-tunes the vessel performance. A large container ship project (14000 TEU carrier) in 2013 employed more than 60 free parameters with the objective of reducing fuel consumption as much as possible, taking into account hydrodynamic power requirements, the specific fuel oil consumption of the respective engines and the ship owner's specific operational profile for speed-draft combinations. More than 35,000 hull shape variants were investigated. For final validation, model tests at the Hamburg Ship Model Basin confirmed the CFD predictions of 4% improvement.

In a project for a Latin American navy, the hull for a new OPV (offshore patrol vessel) design was optimized for power requirements, considering a representative operational profile (six combinations of speed and draft). Constraints came in the form of several hard points for the hull and lower thresholds for initial stability (KM values). In total, 14000 design variants were considered. Overall power requirements were reduced by more than 20%, Fig.4. The unusually high savings can be partially explained by the longer cycles for ship replacement in many smaller navies (sometimes exceeding 30 years). Such large savings are also found for very unusual designs where the designers have no intuitive knowledge or base geometries.

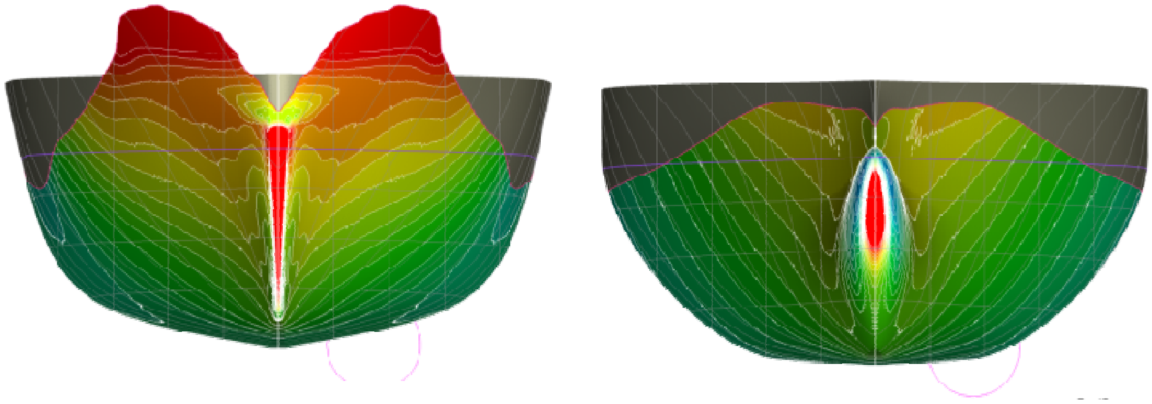

Figure 4: Hull lines optimisation for OPV design; bow wave and bow pressures for original hull (left) and optimized hull (right)

- Bow optimization for refit

  While obtainable fuel savings are significantly larger for complete hull optimisations, optimisation of the bulbous bow region alone still offers very attractive potential fuel efficiency gains. A bow refit project for a 12000 TEU containership may illustrate this, [7], Fig.5 and Fig.6. The parametric model for the bow section alone employed 28 free parameters and 7500 bow variants were investigated. The achieved energy efficiency gains of 10% are higher than for typical bow-only optimisation projects (4-5%), but not uniquely so. Depending on size of fleet, employed repair yard and assumed fuel oil price, there are variations in payback times, but all realistic scenarios show payback times between two and eight months, making refits with optimised bows a good business decision by anybody's standards.

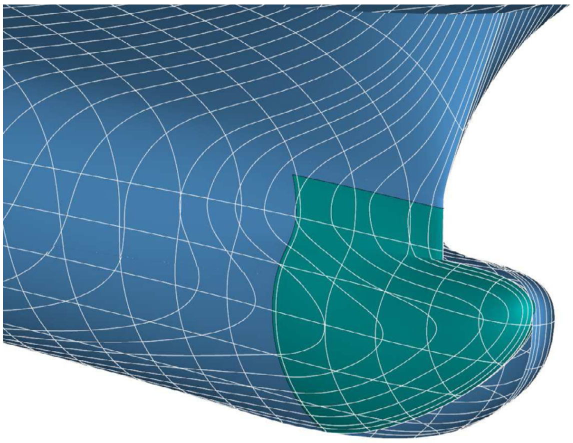

Figure 5: Original (port) and optimised bow (stb.)

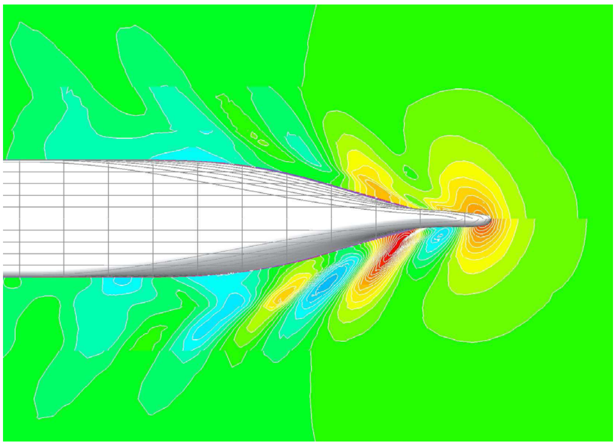

Figure 6: Original (bottom) and optimised bow (top)

2.2 Ship operation

The highest energy saving potential lies in design. However, advanced simulations and optimization techniques are also applied to make ship operation more energy efficient. Key applications in this respect are trim optimization and routing.

- Trim optimization

  In trim optimization, key operational parameters considered are speed and displacement (respectively draft). For most ships, water depth may be neglected. At the heart of any trim optimization software is a knowledge base that relates speed, trim and draft for a given ship to required power. This knowledge base should cover all feasible operational combinations with sufficient data density. Typically this requires 300-400 data sets (combinations of trim, draft and speed), [8]. The discrete data sets are connected by multi-dimensional response surface, allowing consistent interpolation for whatever operational conditions are specified by the user. Today, CFD is the preferred choice to create trim knowledge bases. For some critical cases, such as surface-piercing bows, full-scale CFD calculations are important, [5]. Parallel computations make the CFD approach better respectively more reliable than model tests or system identification based on sensor data, [8].

The approach is then a “simple” optimization application. The shape of the immersed ship is changed by trim and possibly by increasing draft (via ballast water). As a map of the “solution space” is created beforehand, the actual optimization is very rapid and results are displayed immediately for the user, Fig.7. The option to allow larger drafts via ballast water has proven to open better results for modern containerships. These very large containerships operate mostly in partial drafts where the bulbous bow may pierce the water surface creating significant resistance due to breaking waves. Counter-intuitively, adding ballast water can then lead to reduced fuel consumption. For a 13000 TEU containership, the addition of 10000 t ballast water resulted in 5% or 4 t fuel saved per day.

- Route optimization

Route optimization (or routing) has been a topic for research projects for probably 40 years by now. Route optimization for energy efficiency combines weather forecasts (predicting seaways for ocean areas on potential ship routes), ship response to seaways (for energy efficiency, the relevant response is the added power required) and an optimization algorithm. As an added complexity, weather forecasts become increasingly uncertain beyond a time horizon of three days. Assorted constraints (e.g. in the form of strategies of ship owners or charterers) may complicate the optimization problem and explain the diversity found in doctoral theses and service providers.

Realistic estimates for the saving potential of weather routing range from 0.1% to 1.5%, falling significantly short of vendors’ claims. The errors in predicting added resistance in waves are much larger than the claimed savings due to route optimization. Popular methods, such as semi-empirical formulae or strip method approaches, feature errors ranging from 20% to 200%, [9]. This renders weather routing as a most questionable option for fuel savings. Solid arguments for weather routing are rather safety of cargo and crew.

3 CONCLUSIONS

Optimization in ship design and ship operation has progressed from “exotic” research applications to widely accepted state of the art. Refits of ship with bows optimized for current operational profiles may have payback times of less than one year. Trim optimization should be based on full-scale high-fidelity CFD. Ballast water offers additional saving potential for large containerships. Routing for energy efficiency is doubtful, as long as methods for calculating added power in waves feature high errors.

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