WAVE RESISTANCE MINIMISATION IN PRACTICAL SHIP DESIGN

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Summary *A practical and efficient system is described for ship hull form optimisation and its application for minimising wave resistance. Parametric hull form deformations are defined in a CAD system, specific for the case considered and related with flow aspects to be addressed. Surrogate-based global optimisation is applied for multi-objective problems, such as optimisation for a ship's operational profile.*

INTRODUCTION

The wave resistance of a ship at speed in still water is generally known to be most sensitive to hull form variations. Consequently, while not being the largest resistance component for most vessels, it may offer good possibilities for reducing the ship's fuel consumption and is, therefore, always considered in hydrodynamic hull form design. Free-surface potential-flow codes can provide a fast and accurate evaluation for most of the ship wave pattern. Available insight in the physics often permits to reduce the wave resistance by hull form modifications in a stepwise procedure [1,2]. At MARIN, since many years this is frequently supported by analysis of design trends using systematic hull form variations [3].

For fine-tuning, for simultaneous variation of a larger number of degrees of freedom, or for finding an optimal tradeoff between several design points, automatic optimisation offers most useful additional possibilities. Therefore we apply it more and more frequently in practice. The present paper describes the setup of the wave resistance minimisation system that we apply in practical ship hull form design projects. Several hull form optimisation methods have been proposed, e.g. [4,5,6,7]. However, our method has some particular features, having been developed based on the typical use at MARIN:

- In most cases, our work addresses the final hull form design in a later stage of the design process. Main dimensions, main coefficients, LCB and an initial hull form have already been fixed, and several 'hard points' may need to be respected. Therefore, we must be able to make detailed hull form improvements, confined to the design aspects and parts of the hull that may be modified. Flexibility of the parametrisation is therefore essential.
- We have to deal with a large variety of ship types, so we cannot set up a parametric description specific for one class of ships.
- The time available for the wave resistance minimisation is usually 1-2 weeks or less. Thus we need a practical, effective and efficient method to optimise the hull form. Reproducing

the initial design by a fully parametric description or formulating all geometric constraints explicitly would be an undesired preceding step.

This has led us to the present approach, which is characterised by its use of completely general parametric deformations of the initial hull form, in which many constraints are already inherently taken into account; by a focus on parameters that have a direct connection with flow properties we want to address; by efficient evaluation of the objectives using free-surface potential-flow (or free-surface RANS) solvers; and by the use of surrogate-based global optimisation for the frequent multi-objective optimisation tasks. These main components will now be described and some examples discussed.

HULL FORM PARAMETRISATION

Perhaps the least settled aspect of a hull form optimisation is the parametric description of the hull form and its changes. Many possibilities have been proposed. In [8] it is pointed out that the success of an optimisation hinges upon the ability to reproduce by the parametric description, the various shapes that an experienced naval architect would design. This has not always been the case for methods proposed.

The first choice to be made is, whether one tries to represent the entire hull form by a parametric description, or applies parametric deformations to an existing hull form. The former option may seem attractive; but it takes a very large number of parameters to be able to describe whatever ship form, and it remains approximate in most cases. Once the initial hull form provided by a yard would have been reproduced by the parametric description, a part of the parameters could be varied to make modifications; but selecting these and defining all related constraints seems a time-consuming and insatisfactory process. Therefore, we choose the option of parametric deformations of an initial hull form.

Several possibilities have been proposed for this. Some use generic deformations, such as Lackenby shifts [6], modifications of section shapes by Fourier components [9], or additive polynomial surface patches [5]. The advantage of these is that they can quickly be applied and could give a first impression of possibilities for improvement; but they are unlikely to lead to a final, detailed hull form satisfying all requirements. More general are Free-Form Deformation [4,8] or movement of some freely chosen control points followed by Radial Basis Function interpolation of the hull surface [6]. Still these have certain limitations [8]. Also, to apply most of these methods to generate a particular hull form feature would require practical experience. That skill would need to be developed just for this purpose, which we believe is a disadvantage.

However, using a CAD package to create a modification to an existing hull form is a skill that is available. An experienced CAD engineer makes a modification in very limited time, e.g. less than an hour. The resulting hull form is smooth and faired, feasible, has the desired displacement and satisfies the required hard points and some other constraints. At the same time, we have complete flexibility in the type of modification.

Therefore, we use the CAD system to create N deformed versions of the initial hull form. Each represents one particular deformation mode, selected so as to be more or less independent from the others, and normally defines the largest deformation we want to consider. The N deformed versions, together with the original hull form, define an Ndimensional design space of hull forms, of which the NURBS control point positions are interpolated between those of the original and the deformed hulls. The interpolation factors are the N parameters of the hull form family. The hull form variation thus is a parametric blending or morphing of hull forms. There is complete generality, as long as all hull forms are generated by a similar control point network. Fig.1 gives an example of shapes obtained.

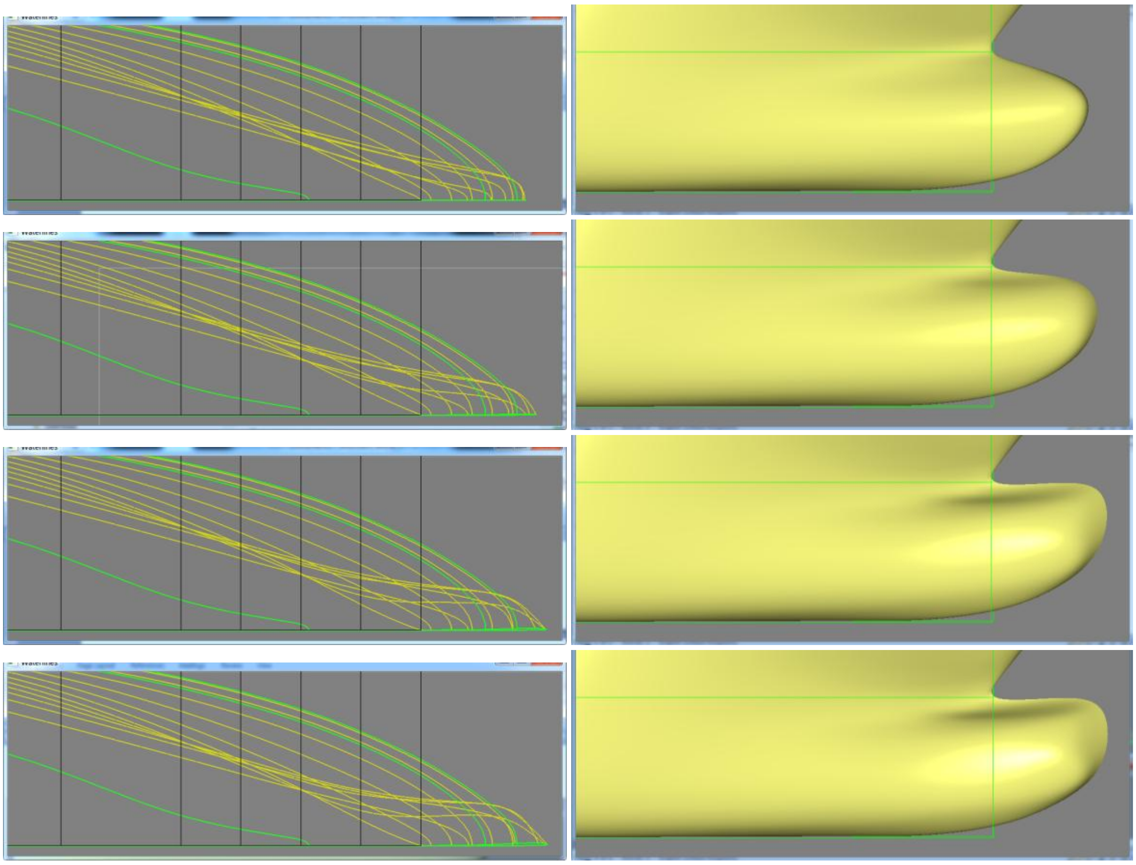

Figure 1 Some bulbous bow shapes generated with 2 parameters: one for contour shape, one for bulb width. The examples have parameter values (0,0) (initial design), (0.5,0.5), (1.0,1.0) and (1.0,1.5)

The most deformed hull forms can be created in the CAD system's fairing mode, or also by additional tools such as an FFD-like method [3] or Lackenby shifts. The amount of work is limited, and is easily compensated by the good quality of the hull forms, the limited number of parameters needed for meaningful hull form changes, and the reduction of the number of constraints needed. E.g. if a local bulb modification to an existing hull form is to be designed, we create modified designs which all match the existing hull form at the position required, and all intermediate shapes will also do so. Similarly, other constraints such as keeping equal displacement and LCB, or trivial issues such as keeping a flat bottom and sides, are incorporated in the deformed shapes and need not be explicitly prescribed as constraints, as they might for generic shape variations.

Once the design space has been created, a hull form and hull panelling can be generated in seconds by a batch command to the CAD system, with the desired parameter values as input.

THE DESIGN SPACE

The freedom to define hull form variations allows, and requires, to make a judicious choice of which to include in an optimisation. We want the parametric changes to be geometrically independent, or orthogonal: a particular hull form should be described just by a single combination of parameters. But also a level of independence of their physical effect is desirable: it would be best if a given trend of the flow field or wave pattern is represented by one or few parameters.

To illustrate, let us consider the action of a bulbous bow. This is strongly determined by the underpressure it creates at its sides, so by the streamline curvature, and its longitudinal location [1]. Suppose a bulbous bow would be described parametrically in terms of the sectional area curve, section shape parameters and a bulb length parameter; these would have just an indirect relation with that curvature, and the response of the bow wave making to these parameters might be an irregular function with more local extrema. Instead, we would typically generate 2 extreme shapes, one with a different bulb length but similar curvature, the other with the same length but different width and curvature. These two parameters would map to the two main physical trends of the bulb action.

In general, we aim at basing the hull form variation parameters on physical effects, and describing those effects with as few and as meaningful parameters as possible. This differs from a purely geometrically-oriented hull form description or deformation, including the Principal-Component-Analysis based method proposed in [10] which seeks to represent with few parameters most of the geometric variability. Instead, our approach is unsystematic but aims for maximum objective variability. Often we assess the sensitivity of the objectives to the parameters beforehand by making computations for some separate hull forms, or systematic hull form variations with subsets of parameters using the RapidExplorer system [3].

Consequently, due to the choice of deformation modes based on hydrodynamic insight, and due to the stage of the design that we typically work in, we often have a limited number of free parameters in the optimisation.

EVALUATION OF THE OBJECTIVE FUNCTIONS

The hull form parametrisation described is being applied with different flow solvers. For viscous-flow related optimisation, we mostly use the Parnassos code, a fast free-surface RANS code [11]. This is also the method of choice if reduction of the stern wave making, for a less slender vessel, is desired. For minimising the required power of ships it is coupled with a propeller representation. Also for this method the optimisation approaches described here have been used and are being further deployed [12].

In this paper however, we focus on the use of free-surface potential flow codes, RAPID [13,14] in particular. This panel method computes the wave pattern and wave resistance by solving the steady nonlinear free-surface potential-flow problem iteratively. After convergence the complete inviscid kinematic and dynamic boundary conditions are satisfied and the dynamic sinkage and trim are incorporated. Rankine source panels are located on the hull surface, and at a small distance above the wave surface. Panel distributions are automatically adjusted between iterations, as are dynamic trim and sinkage. In each iteration, the boundary conditions are imposed in collocation points on the hull and on the last free-surface iterate, and the resulting system of equations is solved by a preconditioned GMRES solver. Usually about 3000 panels on the hull and 5000-20000 on the free surface (per symmetric half) are used, dependent on Froude number. Convergence is typically in 8 to 20 iterations. The RAPID code is usually run on a standard desktop PC and takes from 1 to 10 minutes for the entire computation for one speed.

This code is in continuous practical use in ship design, at MARIN and elsewhere, since 1994. It yields accurate results for a large class of ships, for the wave making from the bow and forebody, fore and aft shoulders, and, for slender vessels, also for the transom stern. For fuller hull forms however, viscous effects play a significant role in the stern wave making and larger deviations occur.

Wave resistance is evaluated both by integration of pressure forces over the hull, and from wave pattern analysis based on a set of transverse wave cuts aft of the ship [14]. The former method is slightly less suitable for optimisation due to some numerical noise from variations in the hull panelling, so mostly the latter value is used as the objective; optionally augmented by a viscous-resistance estimate based on an estimated form factor and a plate friction line. This disregards any variations of the form factor with the hull form variation, which of course is not precise for larger afterbody variations.

THE OPTIMISATION METHOD

After some experimentation with other codes, we have adopted the Dakota package [15], an extensive collection of optimisation tools developed by Sandia National Laboratories. Of its many options, we describe here an approach we have found suitable for our needs so far.

For single-objective optimisation problems, e.g. minimising wave resistance for a single speed and draft, gradient-based methods can work, but tend to be sensitive to numerical noise and some experimentation is required. Different starting points may need to be used to find a global optimum. But in many cases we have to address multiple conditions, e.g. different speeds and drafts, and we resort to other methods. The formal way to balance different conditions in multi-objective optimisation is a major asset for such problems.

For a global multi-objective optimisation, genetic algorithms are a robust choice. However, they often require thousands of objective evaluations, as successive generations converge just slowly to the optimum. Applying a genetic algorithm directly to the solver we found too inefficient. But for the choice of parameters as we make, the dependence of the objectives on the parameters is usually fairly smooth. In that case, surrogate-based methods using response surfaces can work very well. Such methods have also been adopted in [6,16] but without the successive improvement that we apply.

We start with generating a Design of Experiments (DoE), a set of hull form variations spread in a particular fashion over the design space; e.g. a Latin Hypercube Sampling. The number of variations can be quite limited, but a too small number does not help in a later stage. E.g. for a 5-parameter family, we have used 100 variations. For each, the potential-flow code is run for all conditions. Response surfaces are then generated, algebraic functions that interpolate or approximate the objectives as a function of the design parameters. Next, the genetic algorithm is run to carry out the multi-objective optimisation, but it uses evaluations of the response surfaces only, no direct potential-flow computations. Consequently this takes negligible calculation time. For this surrogate-based optimisation, the choice of the actual optimiser is therefore immaterial for efficiency. Any robust global optimiser would do, and our rather conventional choice of a genetic algorithm is no drawback.

The output of this stage is a Pareto-optimal set of variants, but based on the response surfaces. Whether this is a sufficiently accurate approximation needs to be checked. In practice we have noticed RMS errors of 1-5% in the estimated objective functions for these points, so the Pareto front may need to be determined more precisely. Therefore, next the potential-flow code is run for a selection of points on the estimated front, typically 10-20 hull forms in our case. The results of these computations, generally deviating from the objectives interpolated on the response surfaces, are then added to the DoE and the response surfaces are updated. Thus they become more accurate where it matters, i.e. in the vicinity of the Pareto front. We reapply the optimiser using these updated response surfaces, get an improved Pareto front, and may continue this iterative process if needed. In this way, the effect of the chosen size of the DoE and the accuracy of the initial response surface should play no role in the final result, and the Pareto front can be derived extremely efficiently.

However, one needs to survey the process as some of the settings make a difference. A choice to be made is the type of response surface. Dakota supports a variety of options, among which quadratic and cubic polynomial surfaces, or Kriging. An example of how these compare is shown in Fig.2. Clearly there are significant differences; although in this case all response surfaces indicate the same optimum values of parameters. It is, therefore, essential to carry out the step to reevaluate points along the Pareto front to get a true value, and to update the response surfaces and the estimated front. Fig. 2 illustrates the resulting update of the response surface, which is not dramatic but significant.

We also note in Fig. 3 that for one of the intermediate values of the third parameter, the initial response surface has a large deviation at the right front corner, suggesting very low resistance values for those parameters. This appears to be a spurious result, which is only as extreme for the cubic polynomial surfaces. In this case the optimiser does not go to that corner (as a result of the three other objectives taken into account), therefore the updated surface still has the same feature; but in other cases it might cause an erroneous estimated first Pareto front which would disappear in next iterations. On the other hand, a possible pitfall would be if the initial response surfaces overlook a genuine optimum, subsequent refinements occur at another place and this true optimum is never detected. It illustrates that there is a tradeoff in the choice of the size of the DoE.

So far the Kriging response surfaces seem better behaved than the cubic polynomial surfaces. However, if the iterative improvement of the surrogate is continued for more steps, there will be many closely-spaced points near the front which may cause deviations in the Kriging surface, possibly leading to nonconvergence of the front. Kriging is also sensitive to addition of new points due to the Maximum Likelihood Estimation procedure, see [17].

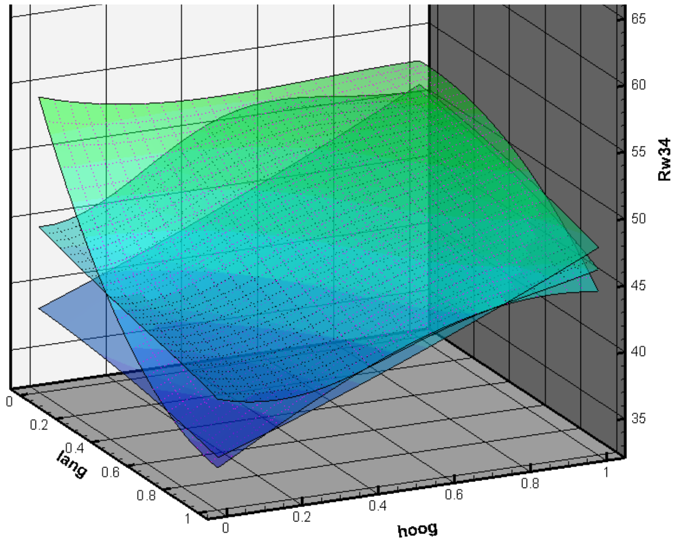

Figure 2 Example of initial response surfaces. For a fixed value of one parameter, the response against 2 other parameters is shown, as derived from the initial Design of Experiments of 40 variants in a 3-parameter space. Top to bottom in the far left corner: cubic polynomial, Kriging, quadratic polynomial.

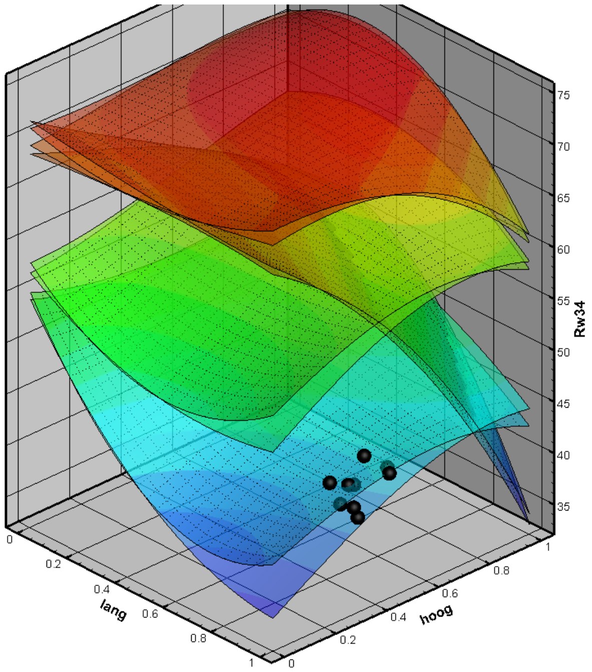

Figure 3 Cubic polynomial response surfaces, before (with mesh) and after update; the markers indicate the added points along the Pareto front.

This surrogate-based optimisation works quite well for our purposes. However, one should keep in mind that we have made particular choices for the parametrisation, with parameters chosen to be related with physical effects, not with geometrical features only; thereby with limited numbers of parameters involved in the optimisation and hopefully, a relatively clear relation with the objectives. This probably contributes to the adequacy of the response surfaces and of the surrogate-based optimisation based on those.

APPLICATIONS

While these methods have been used in several practical design projects, we consider one hypothetical example here, for which more details can be shown. The case at hand is a product carrier as used in the EU-project ‘Streamline’ [11]. Fig. 5 (bottom) shows the computed wave pattern and hull pressure distribution for a speed of 14 kn (Fn = 0.237). We notice rather substantial wave making, with a high bow wave and diverging waves radiated out; a pronounced fore shoulder wave trough, followed by transverse waves along the hull; a substantial transverse wave system aft of the hull, and slight aft shoulder waves. The graph for 11 knots (Fig. 6, bottom) shows much less wave making, but a fore shoulder wave trough at the same position, again transverse waves along the hull, and a diverging bow wave system. Therefore, what needs to be improved for this ship is at least the position and curvature of the fore shoulder; the bulbous bow action, which is now insufficient to reduce the high bow wave; and possibly, some improvements at the aft shoulder, to reduce the steep wave slope towards the transom for 14 kn. While probably too much affected by viscosity for a potential-flow code, we also try to change the transom stern to reduce the transverse wave system aft.

We define 5 parameters:

- A softening and aft shift of the fore shoulder;
- A parameter changing the bulbous bow contour to a more horizontal shape, with simultaneous increase of its length;
- A parameter increasing the width and waterline curvature of the bulbous bow;
- A parameter that shifts the aft shoulder somewhat forward;
- A parameter that lifts the transom slightly and makes the waterline endings more horizontal.

The two parameters for the bulbous bow produce a family of shapes, some of which have already been illustrated in Fig.1. Otherwise these 5 parameters are each related with an aspect of the wave making, and we expect just limited interaction between them.

In this 5-dimensional design space, we generate a DoE of 100 hull form variations, based on Latin Hypercube Sampling. For these rather low Froude numbers the potential-flow computations require a panelling of about 11000, but still a computation time of just 7 min per hull form for 2 speeds, on a single PC; so the DoE can be completed overnight.

In Fig.4 we show the results in a Pareto plot. They appear to be spread around the initial hull form. Response surfaces are then generated, using Kriging, and the genetic algorithm is run to generate a Pareto front, indicated by the open red markers in the figure. The corresponding hull forms are then evaluated by the potential-flow solver, producing the results indicated by the full red markers. Clearly, there is a small deviation between both:

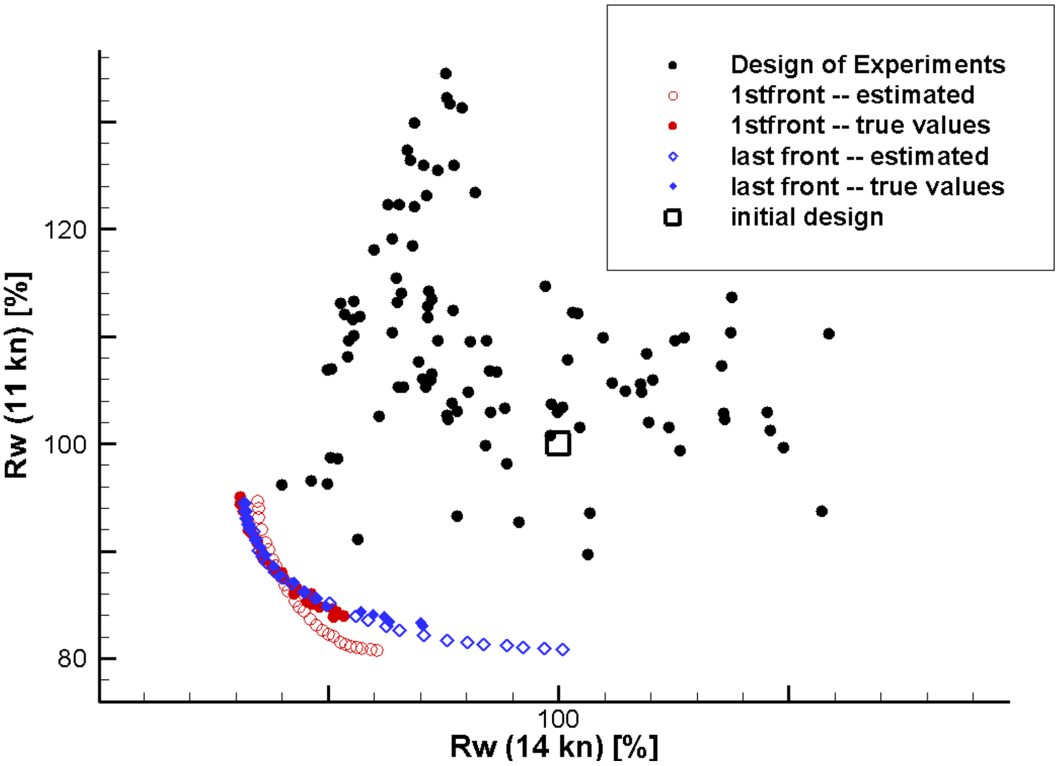

Figure 4 Pareto plot of results for product carrier at speeds 14 and 11 kn. Wave resistance values as percentage of that for initial design (indicated by the black square). Open markers for Pareto fronts found from response surfaces, full markers for corresponding computed values.

the RMS error of the response surface estimates for both objectives in these points amounted to 3.2 and 3.4%, respectively. This is 1/5 of the total improvement relative to the initial hull, so refinement is desired. Subsequently, new response surfaces are built taking into account the DoE plus the new points; optimisation is done on these new surfaces, etc. The blue markers show the Pareto fronts after some of these iterations, for which the estimate and the true values are near identical, errors having been reduced by a factor of 10. In fact, the first true front was already the final one; which means that we had found the optimal hull forms with just 2 * 127 potential-flow calculations.

As appears, about 19% wave resistance reduction has been achieved for 11 knots, 14% for 14 knots with the hull form adjustments allowed here. This amounts to some 6-7% of the total resistance. Figs 5,6 show the wave pattern for the original design and one of the hull forms on the Pareto front, for 14 and 11 kn. There is a clear reduction of the transverse waves along the hull, of the bow wave crest and diverging wave system; and a small reduction of the aft shoulder wave. The transom modification has not really worked though. Still, we conclude that the design space defined was effective, and a significant improvement has already been obtained in very little time (1-2 days).

Various other practical applications have been done. One design question concerned a ferry with a demand for minimum wave resistance at a given higher speed, but a radiated bow

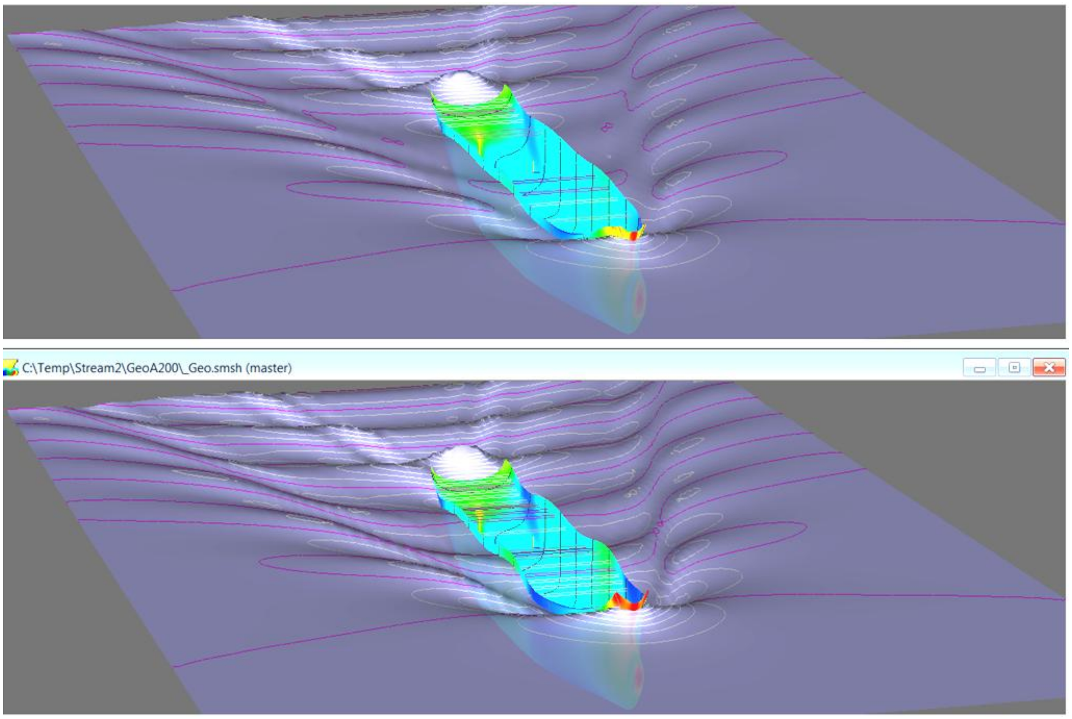

Figure 5 Wave pattern at 14 kn, for optimised (top) and original hull form. Vertical scale 2 times magnified.

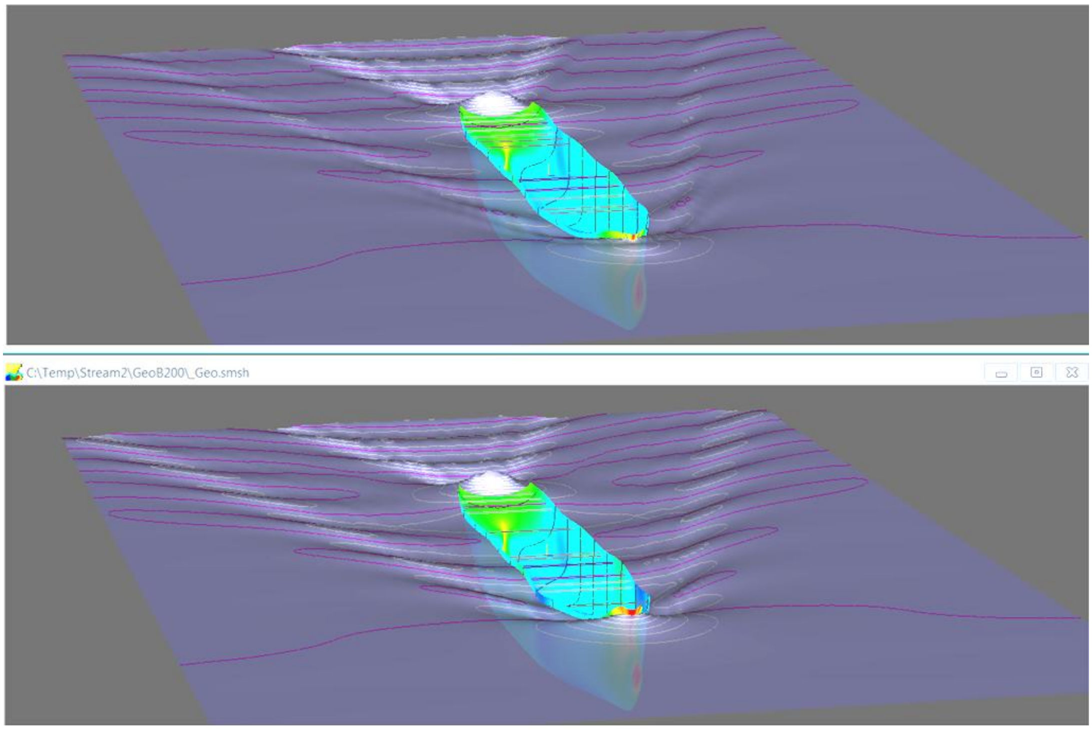

Figure 6 Wave pattern at 11kn, for optimised (top) and original hull form. Vertical scale 2 times magnified.

wave amplitude that had to be reduced to a given upper limit at a lower speed. In that particular case, the problem was succesfully solved as a two-objective problem, minimising the high-speed wave resistance and low-speed wave amplitude. This produced a Pareto front, and the design selected was the point at that front with a low-speed wave amplitude just satisfying the imposed limit (with some margin).

In another project, a containership had to be designed for an operational profile, consisting of 4 drafts and 3 speeds, for which the relative time spent in each condition was provided. We have condensed this to 4 conditions that covered most of the total time, and defined a design space based on extensive preceding sensitivity studies. The optimisation aimed at reducing the sum of wave resistance and estimated viscous resistance, using a constant form factor for simplicity. It led to significantly improved wave making for all 4 conditions. Importantly, the multi-objective optimisation and identification of a Pareto front, followed by selection of the desired hull form using a weighting of the 4 conditions based on time spent and estimated fuel consumption, formed a systematic answer to the request to optimise for an operational profile.

CONCLUSIONS

A practical approach has been presented for minimising ship wave resistance, using a free-surface potential-flow code connected to a CAD system and the Dakota optimisation package. The system is primarily directed at a relatively late stage in the hull form design, when main dimensions, main coefficients and LCB are already known but otherwise the hull form is to be finalised. Hull form variations are obtained by a blending of the original hull form and a number of modified hulls that determine the main axes of the design space. These are simply generated using the CAD system and thus provide complete flexibility. Consequently, there is no need for preset generic hull form modifications as are often proposed; and several geometric constraints can already be taken into account.

The flexibility of defining hull form modifications is exploited by choosing parameters that are directly related with a physical aspect that is to be improved. Thereby, the designer’s skill and hydrodynamic knowledge can be exploited. Also it typically results in a relatively small number of design parameters, and a fairly regular and smooth relation between design parameters and objectives. As a result, adequate response surfaces can be generated based on a rather limited sampling, and surrogate-based global optimisation then appears to works very well. Iteratively updating the response surfaces was found essential.

An example of a 2-objective problem in a 5-parameter space could be solved with just 127 hull forms directly evaluated. The experiences obtained are also being applied in combination with free-surface viscous-flow computations [12], for which an efficiency gain is even more important.

These methods are now used increasingly in practical ship hull form design projects at MARIN, and offer a step forward in the efficiency and effectiveness of the design process.

ACKNOWLEDGEMENT

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REFERENCES

[1] Larsson. L., and Raven, H.C., *Ship Resistance and Flow,* Principles of Naval Architecture Series, SNAME, 2010.
[2] Raven, H.C., Validation of an approach to analyse and understand ship wave making, *Jnl. Marine Science Techn.* Vol.15 - 4, Dec. 2010.
[3] Hoekstra, M., and Raven, H.C., A practical approach to constrained hydrodynamic optimization of ships, *NAV 2003 Symp.,* Palermo, Italy, June 2003
[4] Peri, D., Campana, E.F., Tahara, Y., Takai, T., Kandasamy, M., and Stern, F., New developments in simulation-based design with application to high-speed waterjet ship design, *Proc. 28th Symp. Naval Hydrodynamics,* Pasadena, 2010
[5] Chun, H.H., Hull form parametrization technique with local and global optimization algorithms, *MARTEC 2010 conference,* Dhaka, Bangladesh, 2010.
[6] Kim, H., Jeong, S., Yang, C., and Noblesse, F., Hull form design exploration based on the response surface method, *Proc. 21st ISOPE Conf.,* Hawaii, June 2011
[7] Hochkirch, K., Heimann, J., and Bertram, V., Hull optimization for operational profile --- the next game level. *Marine 2013 Conf.,* Hamburg, 2013.
[8] Brizzolara, S., Vernengo, G., Pasquinucci, C.A., and Harries, S., Significance of parametric hull form definition on hydrodynamic performance optimization, *Marine 2015 Conference,* Rome, Italy, 2015.
[9] Veldhuis,C., Gornicz, T. and Scholcz, T.P., Ship optimization using viscous flow computations in combination with generic shape variations and Design of Experiments, *PRADS 2016 Conf.,* Kopenhagen, 2016
[10] Diez, M., Campana, E.F., Stern, F., Design-space dimensionality reduction in shape optimization by Karhunen–Loève expansion, *Comp. Meth. Appl. Mech. Eng.* Vol. 283 (2015)
[11] Van der Ploeg, A., Starke, B., and Veldhuis, C., Optimization of a chemical tanker with free-surface viscous-flow computations, *PRADS 2013 Conf.,* 2013.
[12] Scholcz, T.P. and Veldhuis, C.H.J., Multi-objective surrogate based hull-form optimization using high-fidelity RANS computations, *Marine 2017 Conf.*, Nantes, France, 2017.
[13] Raven, H.C., *A solution method for the nonlinear ship wave resistance problem*, PhD Thesis, Delft Univ. Techn., 1996
[14] Raven, H.C., Inviscid calculations of ship wave making --- capabilities, limitations and prospects, *22nd Symp. Naval Hydrodynamics*, Washington D.C., 1998.
[15] Adams, B.M., Bauman, L.E., Bohnhoff, W.J., Dalbey, K.R., Ebeida, M.S., Eddy, J.P., Eldred, M.S., Hough, P.D., Hu, K.T., Jakeman, J.D., Stephens, J.A., Swiler, L.P., Vigil, D.M., and Wildey, T.M., "*Dakota, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 6.0 User's Manual,*" Sandia Technical Report SAND2014-4633, July 2014. Updated November 2015.
[16] Rotteveel, E., Van der Ploeg, A., and Hekkenberg, R., Optimization of ships in shallow water with viscous flow computations and surrogate modeling, *PRADS 2016 Conf.,* Kopenhagen, 2016
[17] Dwight, R.W., Han, Z.-H., Efficient uncertainty quantification using gradient-enhanced Kriging, *11th AIAA Non-Deterministic Approaches Conf.,* Palm Springs, California, 2009.