Finding the hull form for given seakeeping characteristics

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ABSTRACT: This paper presents a method to find a hull form that satisfies as good as possible a set of seakeeping requirements. The method uses an initial hull form that is characterized by a set of polynomials that define the beam on the waterline, the draft and the sectional area as a function of the length. The sectional shape is then defined by a 2 parameter Lewis transform. Limits can be supplied to the parameters describing the hull form. The hull form is changed by changing the driving parameters that define the polynomials. The seakeeping behaviour is calculated using a linear strip theory program. An optimization method is used to find the hull form that approaches the seakeeping requirements as good as possible.

The method is applied to the design of a frigate. The required seakeeping characteristics are vertical accelerations that are half those of the original design. The intermediate steps are shown and the final hull shape is presented.

1 INTRODUCTION

Optimizing hull forms to achieve certain objectives is now a well developed branch in science. In the early days this work was restricted to a number of design variants that were tank-tested to have minimum resistance or minimum required power. Today this type of optimization is usually carried out using potential flow solvers; the geometry changes are organized by special software that controls the local hull shape. An example of this work is the optimization of the bulbous bow design (Hoekstra et al. 2003); in most cases the method is tuned to optimization in the advanced design stage where only small changes are possible; nevertheless important reductions of the wave making resistance are then still possible. In the near future this type of optimization can be done using RANSE solvers instead of potential flow solvers.

From the seakeeping point of view, these minor modifications of the hull form are irrelevant: the seakeeping characteristics of the ship will hardly change. Seakeeping behaviour is governed by the overall hull form rather than local details. Apart of this, relatively little is known about what makes a ship a good sea keeper. Original work was carried out by Bales (1980); this was later extended by Walden (1983). Both authors used a series of strip theory calculations and a choice of seakeeping requirements to develop a seakeeping index. This index was then related to hull form parameters by regression analysis. Systematic calculations and experiments were carried out (Blok et al. 1984); the good qualities of the best hull form were allocated to the large longitudinal separation between the centre of buoyancy and the centre of floatation of the waterline. Lloyd (1988) presented results of calculations that showed beneficial effects of wide beam and shallow draft. The results from Blok et al. were later analyzed as resulting from maximizing the water plane area coefficient (Kapsenberg et al. 1998). Funny enough this same publication came up with a design with a very low water plane area coefficient as an optimum for the given seakeeping requirements.

The method in this paper is comparable to Lloyd's method (1988). The idea is to characterize the hull in a limited number of parameters that fix the seakeeping behaviour. Since 'good' seakeeping characteristics are dependent on the tasks the ship has to perform, general advice on what makes a ships hull a good seakeeping one is replaced by direct calculations with specific criteria. The parametric description of the hull form uses no a-priori knowledge; the hull form generation process is organized such that also rather strange hull forms can result. The idea behind this is to determine first what is possible and then to restrict oneself to more 'ship like shapes' and to determine how much of the good seakeeping qualities are to be sacrificed. Such a second stage is also the moment to realize that a linear seakeeping prediction is quite limited and that also considerations like emergence of the bow and slamming on re-entry must be considered. This second stage is not covered in this paper.

2 THE CONCEPT

The basis idea of this development was that seakeeping characteristics of a ship are determined by the gross overall hull shape. This means that a rough description of the ship is sufficient, and that relatively minor modifications can be made later (to improve powering or manoeuvring characteristics) without changing the seakeeping behaviour. A second starting point was the desire to know the required shape regardless of all the other design constraints and subjective criteria related to a ‘good ship’ or ‘current best practice’.

The choice was made to describe ship sections with two parameter Lewis transform. This requires only a description of the design waterline, the draft and the sectional area as a function of the length to have a full 3D description of the hull form. The beam, draft an sectional area as a function of length are each described by two 3rd order polynomials; one for the forward end and one for the aft end. These polynomials are connected to a possible parallel mid body. This results in a set of 21 parameters for a complete hull form definition and would thus result in a 21 dimensional design space.

The original idea was that these 21 parameters would be totally independent, but this proved to be impossible. One of the additional constraints that were put in, was to keep the displaced volume constant. This results in a strong interaction of the parameters describing the SAC. Next to this it appeared to be necessary to have some interaction between the parameters controlling the polynomials for the beam and draft to keep section shapes within the limits imposed by the Lewis transforms. The length between perpendiculars and the displaced volume is kept constant throughout this optimization process.

3 NOMENCLATURE

A	[m^2]	Sectional area
B	[m]	Sectional beam at the waterline
L_{PP}	[m]	Length between perpendiculars
T	[m]	Sectional draft
H_0	[-]	Half beam to draft ratio, $H_0 = B/(2\,T)$
NAA	[-]	Station number aft where constant part of sectional area curve begins
NAF	[-]	Station number forward where constant part of sectional area curve ends
σ	[-]	Sectional area coefficient, $\sigma = A/(BT)$
∇	[m^3]	Displaced volume

4 HULL FORM DEFINITION

The program uses a mathematical hull form description based on polynomials describing the sectional beam, draft and area. These polynomials are defined by the values at the outer ends (at St 0 and 1 or St 19 and 20 respectively) and at the location of their maximum value with a zero longitudinal derivative. The hull form can either have or not a parallel mid body. Initial testing of the software and the hull forms it produced showed that better shapes were obtained using a description by polynomials of the local beam to draft ratio H0 and the sectional area coefficient σ rather than the local beam and draft. The polynomials define values for the beam, draft and area for each of the 20 stations, the shape of the sections is defined by Lewis transforms and this hull form is transferred to the seakeeping program.

The seakeeping calculations require some additional data: the longitudinal position of the centre of gravity LcG and the pitch inertia I_{YY}. The assumption is made that LcG is always the same as LcB and the radius of gyration for pitch is assumed to be 0.25 L_{PP}; this results in $I_{YY} = (0.25 L_{PP})^2 \cdot \rho\nabla$.

The method gives a good approximation of normal hull forms; this is illustrated in Figure 1 which shows the body plan of a standard frigate hull form and the form described by the software using the polynomials and the Lewis forms. Certainly the motion characteristics of the hull form are well characterized by this approximate method.

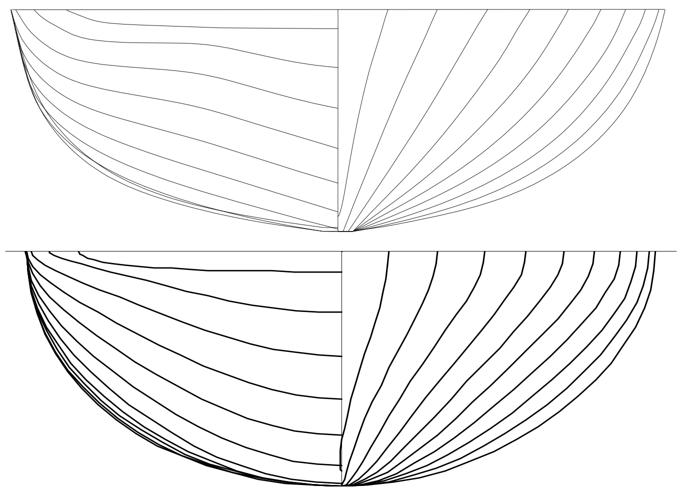

Figure 1 Actual hull shape of the frigate (top) and approximation using Lewis forms.

5 LEWIS TRANSFORMS

The hull form is defined by a 2 parameter conformal mapping method that maps the ship section to a semi-circle. This so-called Lewis-transform is defined by:

$$z = \sum_{n=0}^{2} a_{2n-1} \zeta^{-2n+1} \qquad (1))$$

This formula transforms a circle in the ζ-plane with polar coordinates into a ship-like section in the Z-plane with Cartesian coordinates. The formula describes ship-like sections reasonably well, but at extreme values of the parameters re-entry forms can result. Therefore the following limits to the coefficients were used:

0.04 < H0 < 50.0

For H0 ≤ 1,

σ_{UP} = 1.11735 + 0.0370/H0

σ_{LOW} = 0.58435 – 0.2882*H0 (2)

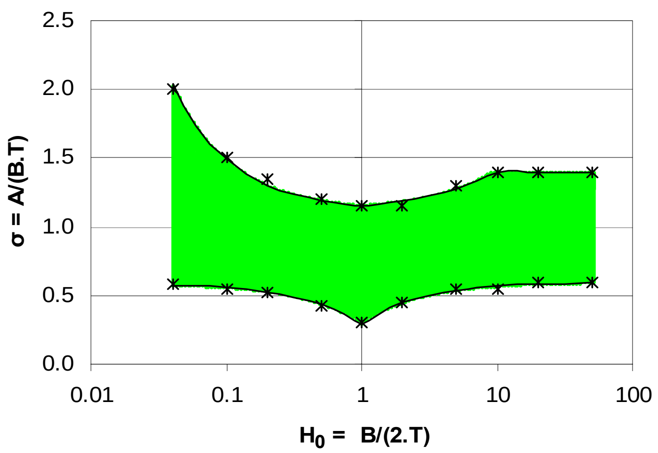

Figure 2 Area (indicated in green) for Lewis transforms that gives ship-like sections.

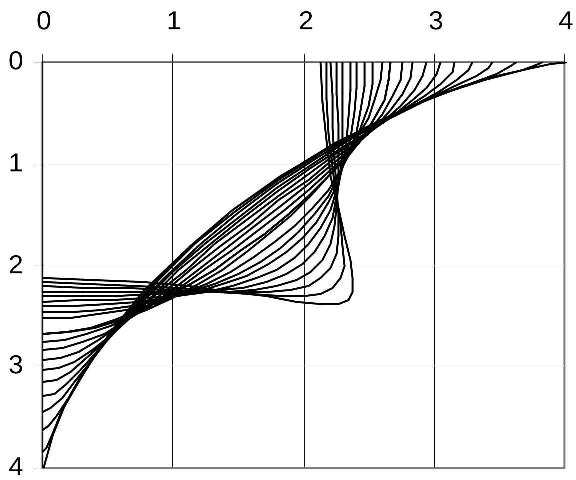

Figure 3 YZ plot of possible section shapes using Lewis transforms. B/(2.T) = 1, 0.30 < σ < 1.10.

For H0 > 1,

σ_{UP} = 1.12435 + 0.0300*H0

with a maximum σ_{UP} = 1.4

σ_{LOW} = 0.59565 – 0.2995/H0 (3)

This area where Lewis transforms of ship sections is applicable is indicated in Figure 2; Figure 3 illustrates that this allows a wide range of section shapes.

6 CHANGING THE HULL FORM

The basic idea was that the hull form could be changed by changing any of the 21 parameters independently. This proved to give undesirable hull forms in the case that a value at one of the outer ends was changed. Due to the choice of the 3rd order polynomial this could resulted in extreme 'overshoots' of the beam, draft or area curves. This problem was solved by creating a weak link between the values of the parameters at the ends: if the value at the ends is changed, the value of the same parameter at the neighbouring section is also changed in the same direction. The step size of this secondary change is 60% of the step size of the primary change. After including this, it appeared to be possible to change the hull form quite radically.

7 CONSTRAINTS

The constraints already listed are those imposed by the Lewis transforms and those imposed on neighbouring sections to keep reasonable hull shapes. Extreme values of the input parameters are also supplied as a constraint on the design space.

Next to this it was decided to keep the length and the displaced volume constant. This second requirement needs some attention because it is allowed to change the Sectional Area Curve (SAC). If one of the 7 parameters describing the SAC is changed, 4 other parameters are also changed according to Table 2. The table indicates (on the first line) that, if the area at St 0 is increased, the area midships and at St 19 is reduced, and that the parallel midbody is shifted aft by reducing NAA and NAF. Changes are made in an iterative procedure that converges to the initial displaced volume.

Initiator	Other parameters that are changed; sign is indicated in brackets			
A0 (+)	AM (-)	A19 (-)	NAA (-)	NAF (-)
A1 (+)	AM (-)	A19 (-)	NAA (-)	NAF(-)
AM (+)	A1 (-)	A19 (-)	NAA (+)	NAF (-)
A19 (+)	A1 (-)	AM (-)	NAA (+)	NAF (+)
A20 (+)	A1 (-)	AM (-)	NAA (+)	NAF (+)
NAA (+)	A1 (+)	AM (+)	A19 (+)	NAF (+)
NAF (+)	A1 (-)	AM (-)	A19 (-)	NAA (+)

8 THE DESIGN SPACE

An initial investigation of the design space is required for the development of the optimization technique. Special care has to be taken if there are many local extremes. Calculations were made changing the beam-draft ratio and the sectional area coefficient midships. The result is shown in Figure 4. The colour indicates the error calculated on the actual vertical acceleration level and the required level. The figure shows that the design space is very smooth and that there are no local minima.

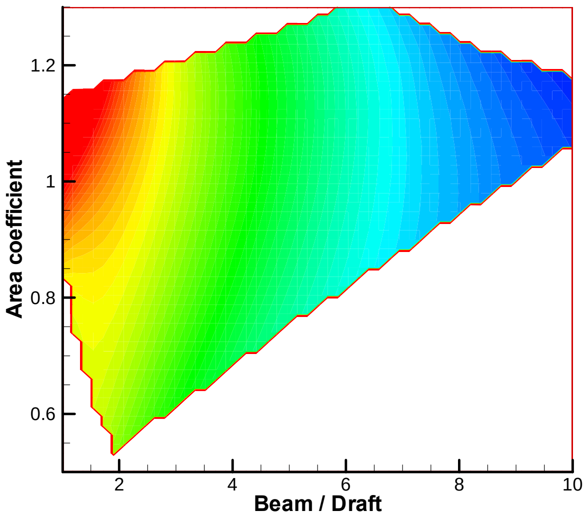

Figure 4 The design space illustrated by changing the beam draft ratio and the area coefficient mid ships. The colour indicates the level of the error function for the design objective (minimum acceleration).

9 THE ERROR FUNCTION

The error function to minimize in the first example is the vertical acceleration on 3 locations: St 0, 10 and 20. The acceleration on the 3 locations is minimized with equal weight; the actual error function is calculated as the square root of the sum of the squares of the error on each location.

As a second example the relative motion at the forward perpendicular is chosen as the error function.

10 THE OPTIMIZATION METHOD

The optimization method that is used to minimize the error function is based on a successive local search and steepest descend method.

The 'Local Search' routine changes each of the 21 parameters individually, changes possible dependent parameters, checks if the hull form is feasible (within constraints of Lewis forms) and calculates the seakeeping characteristics. If one of the checks has a negative result, the variation is not included. The parameter that gives the largest reduction of the error is then selected for the 'Descend' step of the program.

The 'Descend' step finds the maximum reduction that can be achieved by changing just one parameter. Regardless of the success of the 'Descend' step, the program continues with a new 'Local Search'.

If the 'Local Search' routine is unable to find an error that is smaller than the actual error, the step size is decreased and a new 'Local Search' is carried out. The reduction of the step size results in a convergence criterion; in order to check for local minima, a final check on the converged design is carried out with an increasing step size.

This optimization method is not very advanced, but it proved to be a robust method and suitable for the present problem.

11 THE SEAKEEPING PROGRAM

The seakeeping program embedded in the software is a strip theory program with forward speed corrections as developed by Delft University of Technology (Gerritsma et al. 1967). This method has been used for many years and gives surprisingly good results for many hull forms, an application for very fast ships is presented by Blok (Blok et al. 1984). Such a method is extremely fast on present day PC's, the performance is about 1000 calculations (1 speed, 1 wave direction, 15 frequencies) for different hull forms in 1 minute.

12 EXAMPLE MINIMUM VERTICAL ACCELERATIONS

As an example an optimization is carried out for a frigate. The starting point is a hull form that has been used in seakeeping optimization studies before (Kapsenberg et al. 1998), see Figure 1 bottom. The objective was to minimize the vertical accelerations on 3 locations: St 0, 10 and 20 to the minimum (the target was set at 0). The ship is sailing at a speed of 18 kts in a head sea characterized by a JONSWAP spectrum with a peakedness parameter $\gamma = 3.3$ and a zero up-crossing period $T_2 = 7.5$ s.

An optimum is achieved after 80 iteration steps which includes 2165 times a strip theory calculation. The error reduces quite quickly in the first 15 steps; Figure 9, the hull form changes and the error reductions are quite small after this point. The initial steps are used to increase the water plane area forward and to reduce the draft forward. This intermediate result is shown in Figure 5. The vertical acceleration is mostly reduced at St 20 (37% relative to the value for the starting point). For the locations St 10 and 0 this is 22% and 13% respectively.

After 15 iterations much more of the hull form is changed, see Figure 6. The Sectional area Curve is much flatter resulting in a very high prismatic coefficient. The beam is increased over the full length and the draft is reduced. These dramatic changes in the hull shape result in reductions of the vertical acceleration that are 50%, 46% and 52% respectively for St 0, 10 and 20.

If we consider the seakeeping characteristics in more detail, it shows that the largest reduction is due to a lower pitch motion. This is illustrated by the plots of the RAO's, see Figure 10 and Figure 11.

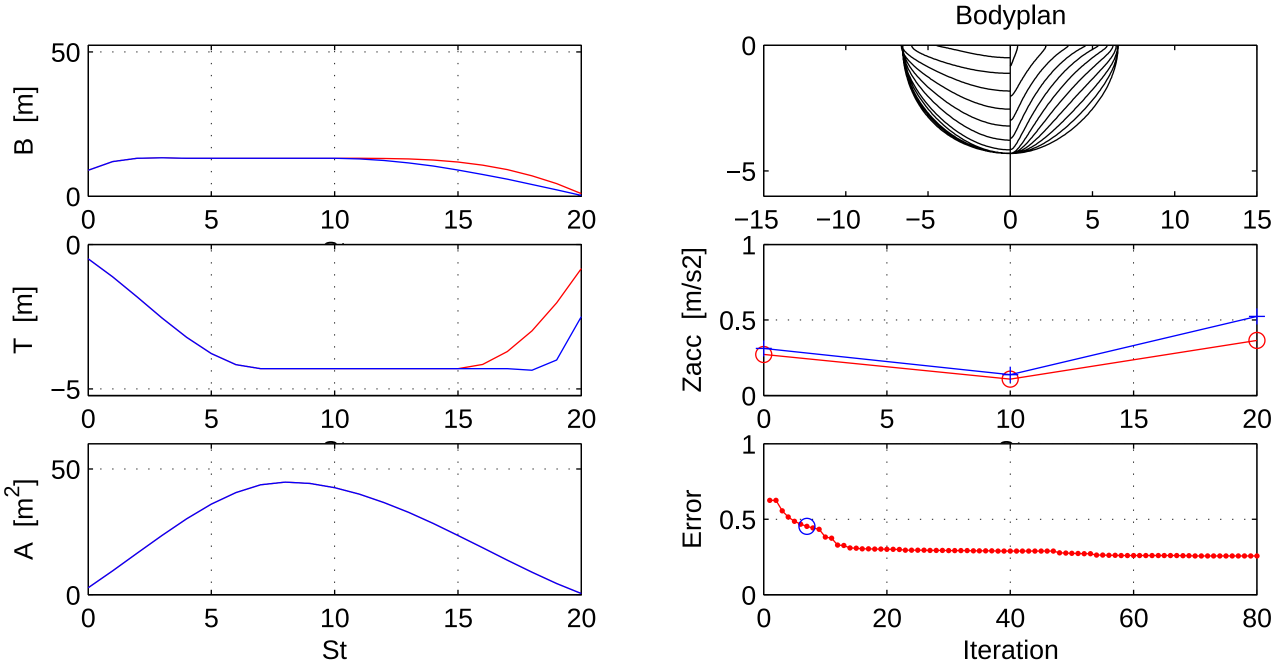

Figure 5 Result after 7 iterations. The new hull form is indicated in red in the beam, draft and vertical acceleration plots; the hull form of the starting point is indicated in red. The body plan is that of the new hull form.

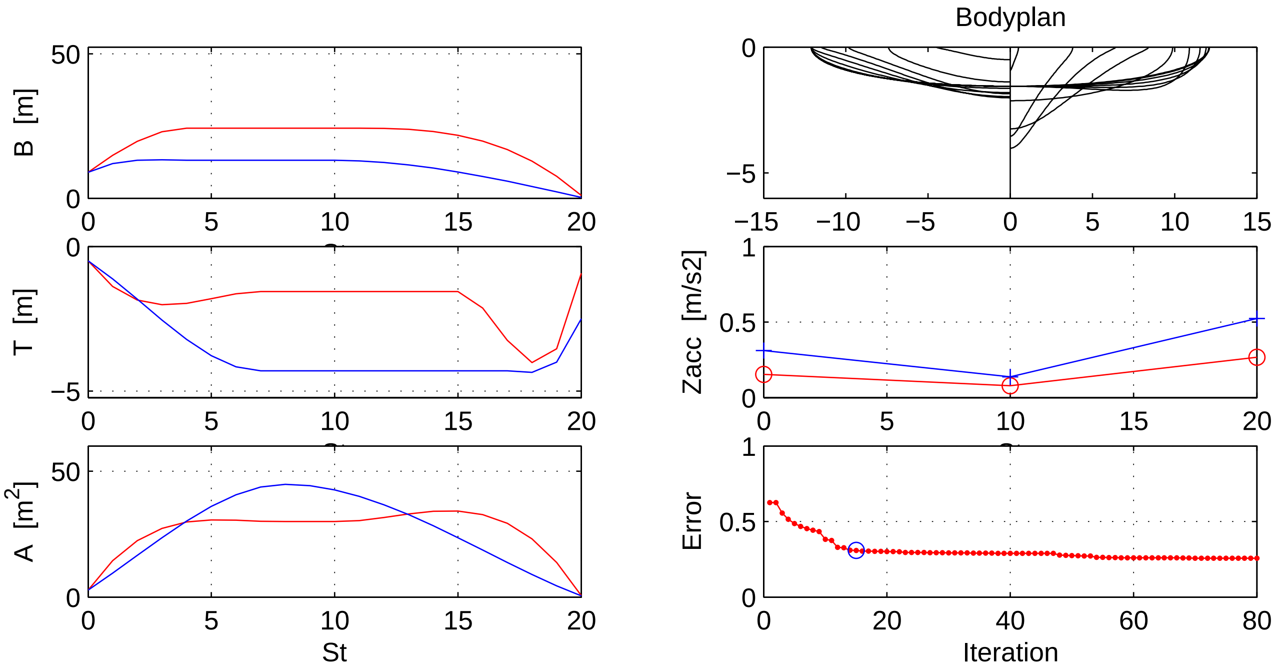

Figure 6 Resulting hull form (in red) after 15 iterations for minimized vertical accelerations. The beam draft and SAC of the starting point is given in blue.

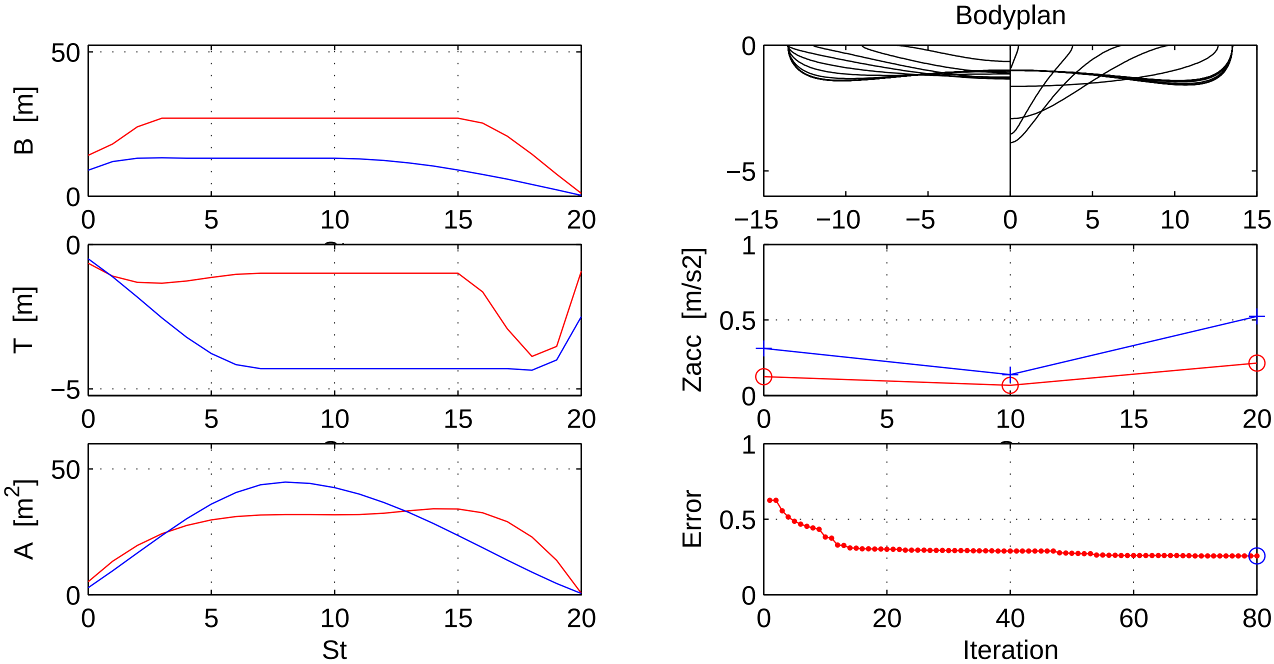

Figure 7 Final hull form for minimized vertical accelerations.

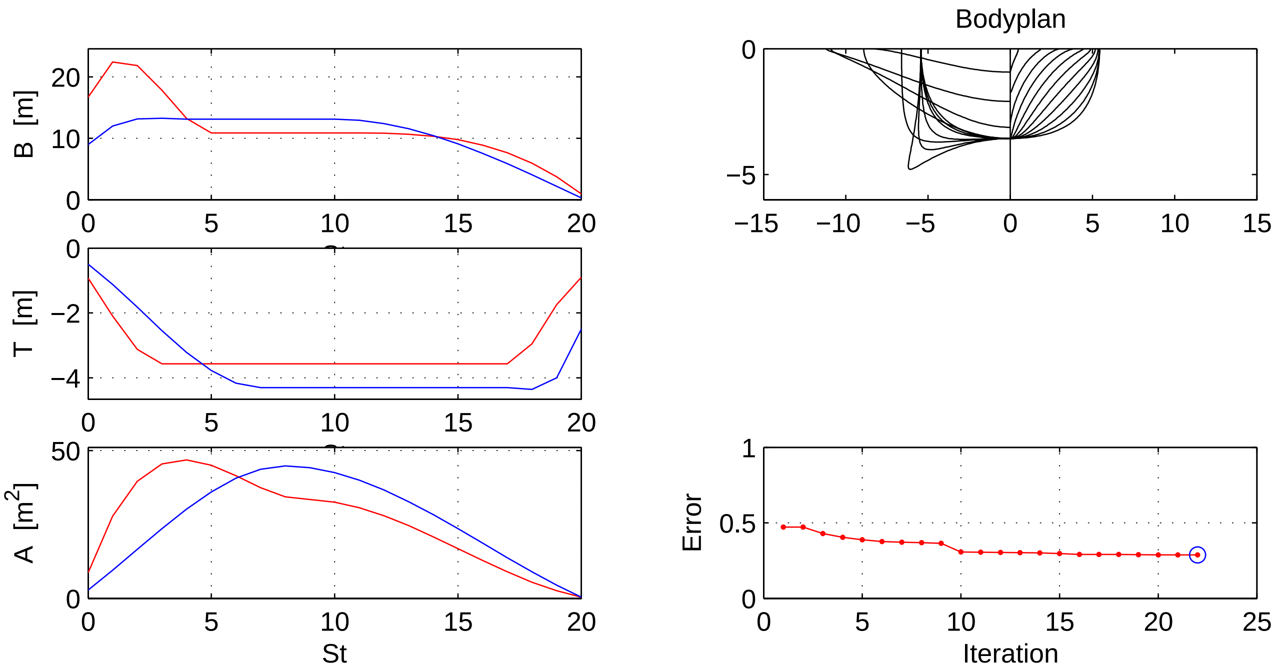

Figure 8 Final hull form for minimized relative motions at the bow.

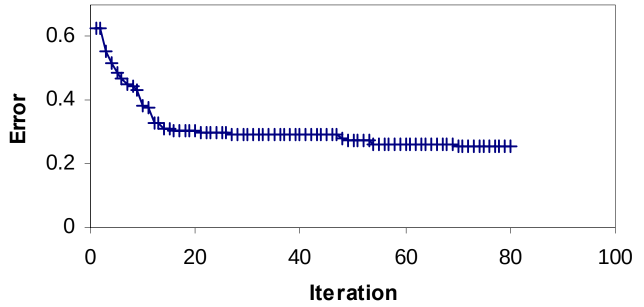

Figure 9 Error as a function of the iteration step.

13 EXAMPLE MINIMUM RELATIVE MOTIONS

The same hull form as used in the previous example has been chosen as a starting point. The error function chosen now is to minimize the relative motions at the bow. In this case it appeared to be possible to reduce the error with 39%. The final hull form is shown in Figure 8. The hull form shows a SAC (and Centre of Buoyancy) that is shifted aft, while the beam of the waterline forward is increased. This results in very hollow sections forward and very wide sections aft. The resulting

RAO of the relative motion at the bow is compared to the same for the starting hull form in Figure 12.

14 CONCLUSIONS

Whether or not the final result of the example calculation is a practical hull form, is not the issue of this paper. The idea is that the software shows in rigorous and objective way the direction to improved seakeeping of ships. Rather than very general trends that are pointed out by studies using systematic series, this method uses the existing hull form and some – user defined - room in the design parameters to find a better hull shape. Next to this the actual seakeeping requirements are directly used. The final hull form is dependent on the requirement that is used in the optimization. Examples are given showing the minimization of the vertical accelerations and the minimization of the relative motions at the bow. Both requirements result in different hull forms as illustrated in graphs and by the values of the main hull form parameters as given in Table 1. This table shows that minimizing the vertical accelerations is achieved by shifting both centre of floatation and centre of buoyancy forward (keeping the separation the same), lowering block and vertical prismatic coefficients and increasing prismatic and water plane coefficients. These results are mainly in line with those from Lloyd (1988).

Optimizing the ship towards reduced relative motions at the bow is achieved by shifting both centre of floatation and centre of buoyancy aft (also reducing the separation between the two), lowering block and water plane coefficients and increasing the vertical prismatic prismatic coefficient. Noted is that the values of the coefficients are dominated by the choice to base them on the maximum values of the relevant parameters.

A warning is given to the user: never fully trust the results from computer programs. Even if the code has been written free of bugs, there are assumptions made in the theory; it is a model of the real world, not the real world itself. In this case it must be realized that the 'heart' of the software is a linear seakeeping program. The results must be used as an indication of the direction in which to change a hull form. It is quite obvious that the final

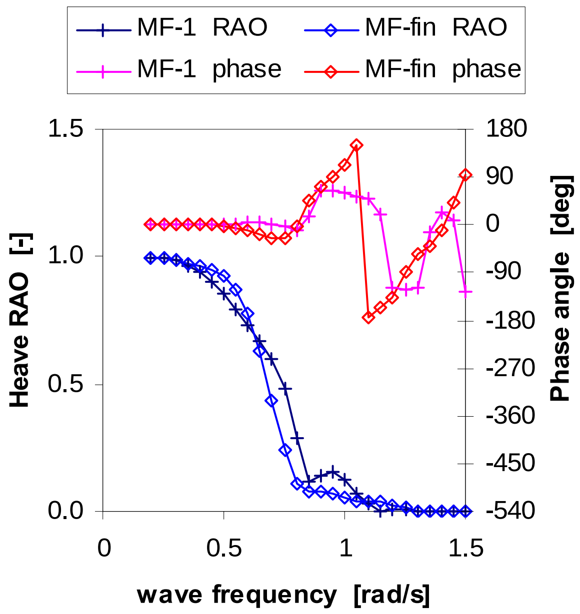

Figure 10 Heave RAO and phase angle of the hull form at the start of the optimization (MF-1) and at the end of the procedure (MF-final).

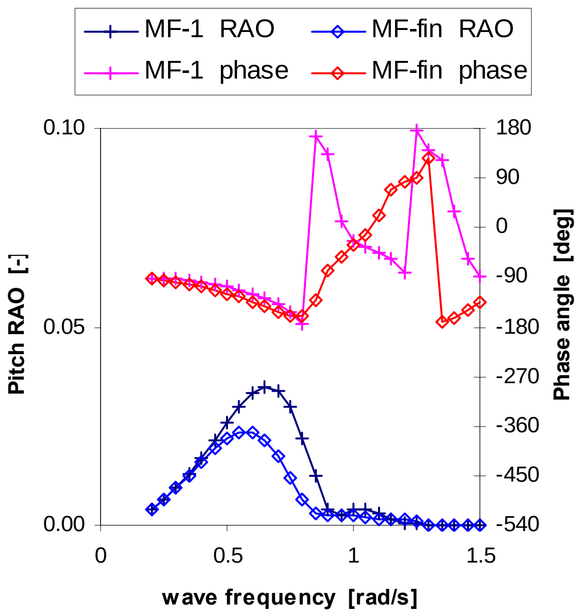

Figure 11 Pitch RAO and phase angle of the hull form at the start of the optimization (MF-1) and at the end of the procedure (MF-final).

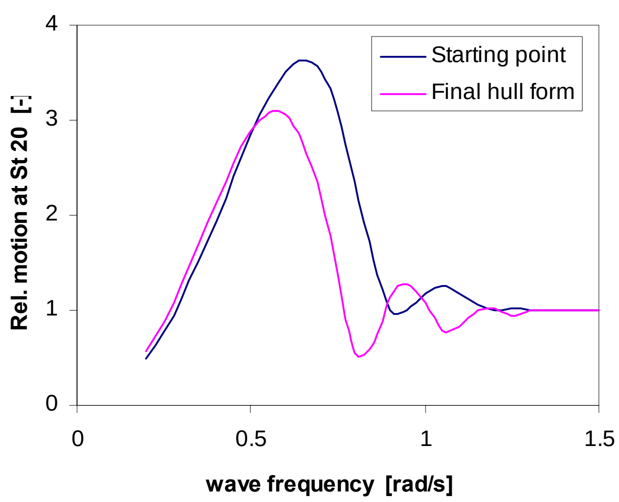

Figure 12 Relative motion at the bow of the hull form at the start of the optimization and the result for the final hull form.

hull forms that are presented in this paper with their shallow draft will not be good seagoing ships; for instance the hull will be prone to severe slamming in rather low waves.

The main use of the method presented in this paper is – as we see it – two fold: By doing an optimization with a large design space, one gets an idea of the main features of a hull form that is optimized with respect to seakeeping only. These results can be used in an early design phase. The second way of using the method is in the advanced design phase when the freedom to changes the hull form is limited. The method can then indicate the most effective change in the hull form to further improve seakeeping.

Parameter		starting point	Min accel	Min Relmo
Length perpendiculars	L_{PP}	114.10	114.10	114.10
Maximum beam	B_{MAX}	13.14	27.04	22.40
Maximum draft	T_{MAX}	4.30	3.87	3.57
Displacement	Displ	3110	3088	3089
Longitudinal centre of buoyancy (fwd of APP)	LcB/L_{PP}	0.4619	0.5108	0.3804
Longitudinal centre of floatation (fwd of APP)	LcF/L_{PP}	0.4211	0.4697	0.3946
Block coefficient	c_B	0.4822	0.2585	0.3390
Prismatic coefficient	c_P	0.6079	0.7935	0.5779
Vertical prismatic coefficient	c_{VP}	0.5972	0.2974	0.6631
Water plane coefficient	c_{WP}	0.8075	0.8691	0.5113

Table 1 Main hull form parameters of starting point and the two optimized hull forms. Coefficients are based on maxima for beam and draft.

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