Hull Form Optimization for Hydrodynamic Performance

Article *in* Marine technology · October 2004

Gregory Grigoropoulos
National Technical University of Athens

HULL FORM OPTIMIZATION FOR HYDRODYNAMIC PERFORMANCE

By Gregory J. Grigoropoulos, Associate Professor NTUA

ABSTRACT

A method for optimizing of hull forms with respect to their hydrodynamic performance in calm and rough water is presented. The method is based on an initial optimization of a parent hull form for seakeeping and the improvement of the resulting optimum hull form for calm water resistance. In the first part of the method, variant hull forms differing from a parent in the main dimensions and/or in one or more hull form parameters such as C_{WP}, LCF, C_B, LCB, KB, C_P are automatically generated and their seakeeping qualities evaluated. When appropriate ranges for the principal characteristics and parameters of the hull form under investigation are prescribed, a formal optimization procedure is used to obtain the variant with the best seakeeping behaviour. The weighted sum of the resonant values of selected ship responses for a number of ship speeds and headings in regular waves forms the objective function. Hooke & Jeeves Algorithm is used to accomplish the optimization. The procedure results in a set of trends regarding the proposed variations of the selected hull form parameters, within the specified constraints. These trends are then applied on the parent hull to derive an optimized hull form with fair lines. Subsequently this hull form can be locally modified to improve its calm water resistance or, as it should be done, its propulsion characteristics.

The applicability of the method is demonstrated in two cases: a conventional reefer ship and a naval destroyer. Scaled models of the parent and the optimized hull forms have been tested for calm water resistance and seakeeping. In both cases the validity of the methodology is demonstrated.

1. INTRODUCTION

Fifty years after the development of the first practical strip theory by Korvin-Kroukovsky (1955), analytical seakeeping prediction methods are widely used for the evaluation of the seakeeping qualities of ships. Twenty-five years ago, Bales (1980) published a paper treating the optimization of the seakeeping performance of Destroyer-type hull forms, based on the analytical predictions. By that time the analytical tools available to the profession were considered reliable enough to be used for optimization purposes, in contrast to seakeeping experiments which cannot be practically used for the same purpose, due to excessive time and cost involved. Bales used analytical results to derive a regression formula correlating the performance of this type of ships in head seas and at various speeds to certain empirically selected hull form parameters.

Grigoropoulos and Loukakis (1988) presented a new method for developing hull forms with superior seakeeping qualities. The new method, described in Grigoropoulos (1989), was used for the analytical development of an optimized hull form for a reefer ship. Models of both the parent and the optimum hull forms were tested at the Towing Tank of the National Technical University of Athens (NTUA) and the analytical optimization procedure was experimentally verified.

In this paper, the aforementioned method is further extended and improved to take advantage of modern computer-aided design (CAD) and Computational Fluid Dynamics (CFD) tools, currently available to the profession. Utilizing these tools, the hull form of a modern destroyer was optimized with respect to both its performance in calm water and in waves. Model tests with the parent and the optimized hull forms verified the efficiency of the optimization methodology. Furthermore, additional calculations for the reefer vessel have been carried out, extending the optimization gains.

2. HYDRODYNAMIC OPTIMIZATION IN SHIP DESIGN. THE NEW METHOD

In most designs of merchant and naval ships, the main parameter to minimize is resistance (or rather SHP) at a given service speed. Model test and CFD tools are used in this respect. Potential flow codes are used in optimizing wave resistance by evaluating variants of the fore and middle body of hull forms (Valkhof et al, 1998), while RANS solvers should be used for the stern region where viscous effects are dominant. However, the necessary modifications for improving resistance can contradict the requirements for optimum propulsive performance. In addition, RANS solvers are still quite complicated and cumbersome to be incorporated in an automatic or even semi-automatic optimization process. On the other hand, model tests can practically be carried out only for the parent and the optimum variant.

Although seakeeping is not usually a dominant parameter in the design process, especially for merchant ships, the incorporation of superior seakeeping qualities in a new ship design is obviously desirable. According to recent studies (see for example, Hearn et al, 1992), seakeeping considerations can and should be incorporated from the beginning in the design procedure. On the other hand, there is also room for considerable seakeeping improvements even when the displacement and the principal characteristics of a new design have been determined without any seakeeping considerations, as it will be demonstrated.

The proposed methodology has been developed with the above two application areas in mind. That is it can either be incorporated directly in the preliminary design spiral or it can be used to modify a parent hull form. In both cases the objective of the new procedure is not to ensure, for example, that a specific dynamic response of the hull form does not violate a specific seakeeping criterion at a given speed and in specified sea conditions. The objective is to ascertain that a ship, designed with a very complex objective function and many practical constraints in mind, will have as good seakeeping qualities as possible.

Seakeeping optimization is known (see e.g. Walden et al, 1985) to result in somewhat increased resistance. As it is demonstrated in the second of the applications of the proposed methodology, the hull form optimized for seakeeping is amenable to subsequent refinement by applying local modifications to improve its resistance characteristics. These modifications may further improve its seakeeping performance as well. On the other hand, as it will be discussed in this paper, the interplay is not really between seakeeping qualities and ship resistance. Rather, the real problem is how to ensure good propulsion characteristics both in calm water and in waves, coupled with good seakeeping performance. That is, the propulsion unit of the ship and its interaction with the hull should be included in the optimization scheme, although this is a much more difficult problem.

3. DESCRIPTION OF THE METHOD

The original method for optimizing hull forms for seakeeping has been described in detail by Grigoropoulos (1989) and Grigoropoulos and Loukakis (1988). However, for the sake of completeness, the main tools and assumptions of the method and a brief description of the formal optimization scheme will be presented in this section, together with the recent amendments to the method to accommodate resistance optimization.

3.1 Hull Form Description

The hull form should be described in adequate detail for seakeeping calculations, but in a simple manner to allow for the automatic generation of the many variants required by the optimization scheme. Thus, the hull form is considered to be known if the following characteristics are specified: the main dimensions L_{BP}, B and T, the sectional area curve S(x), the waterline curve B(x), the longitudinal profile curve Z(x) and the curve of the longitudinal distribution of the centroid of the ship sections KB(x), Athanassoulis and Loukakis (1985).

From these curves, all necessary ship design parameters can be derived i.e. Δ, C_B, C_P, C_M, C_{VP}, C_{WP}, LCB, LCF, KB etc.

3.2 Hull Form Variants.

The first step in the optimization process is to derive an optimized hull form with respect to seakeeping performance. Since the modifications necessary for seakeeping refer mainly to global hull form parameters, variants of the parent hull form are automatically generated. In this respect the method proposed by Lackenby (1950) is used, suitably extended to accommodate waterlines and sectional area curves of any shape. A very important feature of the code is that it allows for the independent variability of any of the following six form parameters: C_{WP}, LCF, C_B, LCB, C_M and KB. Thus, variant sets of hull form parameters differing in one parameter only can be generated and by successive applications of the method, prescribed sets of hull form parameters can be obtained. Although these sets of hull form parameters do not necessarily correspond to a practical faired lined hull form, they provide guidance to the modification of a parent hull form or to the generation of a hull form by Computer-Aided Ship Hull Design (CASHD) methodologies, as e.g. those proposed by Pigounakis (1997), Harries (1998), and Bloor and Wilson (1999). Similar methods are currently embodied in commercial CAD software as TRIBON M2 (Kockums, 2002) or AUTOSHIP 7.1 (Autoship System Corp., 1999).

3.3 Analytical Tools for Seakeeping and Resistance Calculations

The strip theory method of Salvesen, Tuck and Faltinsen, S-T-F (1970) is used for the calculations, coupled with a three-parameter extended Lewis-form representation of the ship sections (Athanassoulis and Loukakis, 1985), which takes into account the centroid of the section. As is well known, strip theory remains a solid basis for seakeeping calculations and competes successfully with newer and more rigorous methods (Bailey et al, 2000, Grigoropoulos et al., 2000), even at high speeds, when compared with experimental (Blok and Beukelman, 1984) and full-scale results (Grossi and Dogliani, 2000). The usefulness of strip theory is more pronounced in the prediction of the shape of the RAO curve in the vicinity of the resonance for the vertical ship responses (Bruzzone et al, 2000), which is essential for the proposed optimization procedure. In the usual two-parameter Lewis-form representation of ship sections, the beam, the draft and the sectional area describe the section. The aforementioned description of the hull form includes a third parameter KB(x), the centroid of the section. In this manner, a more detailed description of the hull form is available, which has been found to give quite similar results to close-fit hull form representation (Frank, 1967), without the need to completely describe the ship surface.

In addition, a recent three-dimensional panel code SWAN2-2002 (Kring and Sclavounos, 1995) is used to assess the calm and rough water performance of a hull form. However, this code is time-consuming and requires a precise description of the hull form, which can be prepared following a tedious work either by applying manual fairing or by using a CAD system, under the assumption that the shape of the hull form including its geometrical details is well established. However, this is usually not the case in the preliminary design phase, when hull form optimization for seakeeping is required. Thus, in the proposed method 3-D codes are used a posteriori for the hydrodynamic evaluation of the parent and the optimized resultant hull forms.

On the other hand, a variety of linear or non-linear potential flow codes can be used to estimate the wave resistance of the parent and the optimized for seakeeping hull forms, i.e. the SHIPFLOW code (FLOWTECH, 1999) or the SWAN2-2002 code. The numerical investigation of the calm water performance reveals regions of poor flow characteristics, which the designer can remedy prior to the construction of the scaled models.

Finally, since the term “accurate” to describe the seakeeping responses is used traditionally in a loose sense, careful experimental verification of the actual advantages of the optimized hull forms is required.

3.4 The Figure of Merit

To obtain an optimum solution a figure of merit should be specified. In contrast to other methods, which in general use the seakeeping performance in sea states to define a figure of merit, the present method postulates that:

> “Ship responses at sea are minimum when the corresponding peak value of their Response Amplitude Operator (RAO) is minimum" and

> that, therefore, seakeeping optimization can be achieved on the basis of regular wave results only."

Numerical computations have shown that this assertion is true for ships with displacement and dimensions close to those of the parent hull form.

However, the magnitude of the peak value of the relative vertical motion RAO is not adequate to describe seakeeping events related to the underwater part of the hull, as bottom slamming and propeller emergence. Thus, these events cannot be explicitly included in the optimization process and the corresponding performance of the optimum hull form can be established only a posteriori. This is only a slight shortcoming when draft is kept constant or is changed only a little from the parent, because the minimization of the relative motion provides a strong indication that the severity of the corresponding seakeeping events will also be reduced.

3.5 The Optimization Problem

With the previous discussion in mind, the optimization problem can be stated as follows:

> "Find the variant with the optimum seakeeping performance of a parent hull form, described by a set of four curves S(x), B(x), Z(x) and KB(x) and identified by a set of design variables (L_{BP}, B, T, C_B, C_{WP}, LCB, LCF, KB) under given constraints."

Seakeeping performance is expressed as the weighted sum of the peak values of a prescribed set of ship responses in regular waves, for various ship speeds and headings. Optimum performance corresponds to the minimum value of this sum, which is the objective function of the problem.

The constraints to be included in the optimization problem are classified in the following two categories:

a. Equality conditions established by hydrostatic and stability considerations or economical reasoning.
b. Inequality constraints imposed by common design practice limitations.

In the first class of constraints the following relations are included:

- The relation between the displacement, the main dimensions and the block coefficient:

$$\Delta = C_B\, L_{BP}\, B\, T = \text{constant}$$

- Geometrical relations that hold between the various form parameters, i.e.

$$C_B = C_{WP}\, C_{VP}$$
$$C_B = C_M\, C_P$$

In the second class of constraints the following inequalities should be taken into account for reasons shown in parentheses:

- $LCB_1 \leq LCB \leq LCB_2$ (trim)
- $C_P \leq C_{P0}$ (calm water resistance)
- $GM \geq GM_{MIN}$ (transverse stability)
- $C_{WP1} \leq C_W \leq C_{WP2}$ (deck space, calm water resistance)
- $C_M \leq C_M \leq C_{M2}$ (calm water resistance)

Usually, in the preliminary design phase a vertical position of the centre of gravity is assumed. Thus, the requirement regarding the transverse stability leads actually to a restriction on the vertical position of metacenter KM, i.e.

- $KM = KB + BM \geq KM_{MIN}$ (transverse stability)

The following characteristics of the optimization problem can help in selecting the appropriate optimization method:

- the non-linearity of the constraints
- the existence of both equality and inequality constraints
- the unimodality of the object function, experimentally verified by setting up the optimization procedure from different starting points and reaching the same result
- the continuous character of all decision variables.

On the basis of the above, the direct optimization method proposed by Hooke and Jeeves (1961) in conjunction with the External Penalty Function Method (Wangdahl, 1972) has been selected. The External Penalty Function Method is used to convert the constrained optimization problem to an unconstrained one and is more efficient than the Internal Penalty Function Method. The method of Hooke and Jeeves is simple to program and has found to be very effective for the particular optimization problem in comparison to other direct search methods.

4. APPLICATION OF THE METHOD

The optimization procedure has been applied in two cases, a reefer and a destroyer hull form. As explained in the previous sections, the hull forms developed by the computer code do not possess (fair) ship lines. The representation of their cross sections is the one provided by the three-parameter Lewis-form. Thus, when the optimization procedure has yielded an "*optimum*" hull form, a set of ship lines, incorporating as many of the characteristics of the analytical calculations as possible, should be developed using CAD fairing software (or even manually). Obviously, the seakeeping characteristics of this final hull form denoted as "*faired optimum*" will be somewhat inferior to the optimum.

For both cases treated, the objective function of the optimization procedure was chosen as the sum of the peak RAO values for vertical acceleration and relative motion at a point 0.1 L_{BP} behind the forward perpendicular, in head waves. The former accounts for the seakeeping operability indices currently in practise to quantify the effect of seakeeping responses on humans (see for example Grossi et al, 1998), while the latter is related to the seakeeping events (slamming, deck wetness etc.). Other responses with RAO curves exhibiting resonance, as added resistance in waves could also be included in the optimization function. However, since added resistance depicts trends similar to those of vertical acceleration and relative motion, its incorporation in the object function does not really affect the outcome of the optimization procedure. This fact has been verified in both test cases.

4.1 The Reefer Ship Case

The experimental verification of the optimization procedure was first (Grigoropoulos and Loukakis, 1988) tried on the hull form of an existing 93.4 m long reefer ship, which was optimized with respect only to secondary hull form parameters, i.e. C_{WP}, LCB, LCF and KB. In this way the contention that even with constant principal characteristics the seakeeping performance of a ship can be significantly improved, could be validated. A reduced speed (V_S = 14 kn) to the design speed of the vessel (V_S = 17 kn) has been selected for the optimization.

It should be noted that the small bow bulb of the parent design was excluded from the optimization procedure, to avoid problems associated with its modelling within the automatic optimization procedure. Furthermore, although the bow bulb is primarily fitted for improving the resistance characteristics of the vessel, it could also be optimized for seakeeping in a subsequent optimization scheme, where its design parameters (Blume and Kracht, 1985) would be varied.

The principal and secondary hull form characteristics of the parent, the optimum and the (manually) faired optimum for the reefer vessel are shown in Table 1. In this table the calculated RMS values of the Absolute Vertical Acceleration (AVA) and the Vertical Relative Motion (RVM) at a point 0.1 L_{BP} aft of the Forward Perpendicular (FP) for the parent and the optimized hull forms are given. The seakeeping results pertain to the ship sailing at 14 knots in head waves with a significant wave height $H_{1/3}$ = 1 m, since the calculations are linear, and a modal period T_P = 10 sec, corresponding to the worst case (see Figs. 14 and 15).

The constrained secondary hull form parameters were allowed to change during the optimization as follows:

$$\delta(LCB, LCF) = \pm 0.04\ L_{BP},\ \delta C_{WP} = \pm 0.04\ C_{WP},\ \delta KB = \pm 0.02\ T$$

From the contents of Table 1 it can be seen that in order to obtain an optimum hull form the procedure increased C_{WP}, shifted LCF forward and shifted VCB downwards, all as much as allowed. It also shifted LCB forwards but only by 0.01 L_{BP}.

The optimized hull form had a considerable reduction in both RMS AVA and RVM in comparison to the parent by 19% and 21% respectively. However, when a set of ship lines had to be produced, not all characteristics of the "optimum" hull form could be retained and the faired optimum hull form was developed for which the reduction of the aforementioned responses was 13% and 16% respectively. The body plans of the parent and the faired optimum hull forms are shown in Fig. 1. Isometric views of the hull forms are shown in Fig.2.

Table 1

Characteristics of the parent and the optimum reefer hull forms at V_S = 14 kn. (The volume of displacement is 6103 m^3 and the draft 6.50 m in all cases.)

CASE	L_{BP} [m]	B_{WL} [m]	WS [m^2]	C_B	C_M	C_{WP}	LCB [%L_{BP}]	LCF [%L_{BP}]	KB [m]	AVA [m/s^2]	RVM [m]
REEFER PARENT	93.40	17.00	1953	0.577	0.974	0.770	-3.23	-5.04	3.62	0.514	0.544
REEFER OPTIMUM	93.40	17.00	-(*)	0.577	0.985	0.809	-2.33	-0.98	3.49	0.416 –19%	0.430 -21%
REEFER FAIRED OPTIMUM	93.40	17.00	1979	0.577	0.979	0.790	-1.67	-1.24	3.64	0.448 –13%	0.455 -16%
REEFER OPTIM-1	89.90	16.20	-(*)	0.634	0.985	0.899	-2.21	-1.23	3.49	0.373 –27%	0.405 -26%
REEFER OPTIM-2	98.10	16.20	-(*)	0.577	0.974	0.770	-3.23	-1.46	3.62	0.445 –14%	0.446 -18%

(*) ***Note:*** The wetted surface is provided only for the hull forms possessing ship lines.

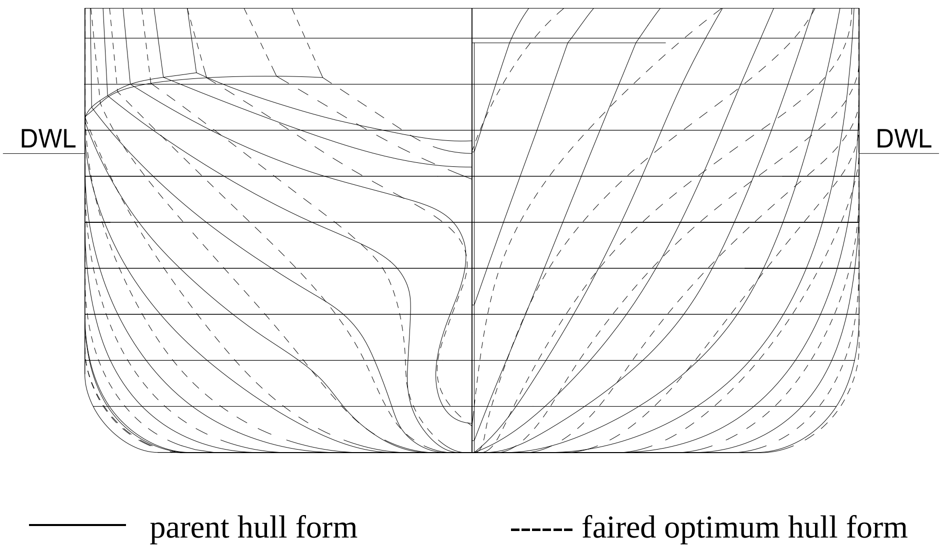

Fig. 1: Body plan of the parent and the faired optimum hull forms.

To further demonstrate the use of the method, the optimization was performed on the reefer hull form under the following constraints:

Δ, T = constant, $\delta L_{BP} = +0.05\, L_{BP}$, $\delta B = +0.05\, B$
$\delta C_B = +0.1\, C_B$, $\delta KB = +0.02\, T$, $\delta(LCB,LCF) = +0.04\, LCB$

In this case no restriction was imposed on C_{WP} but the waterplane area was allowed to increase by up to 7%.

The results of this optimization are also shown in Table 1, where the case is denoted as "REEFER OPTIM-1". In this case the optimization has yielded a shorter, less beamy and fatter ship, with a very large waterplane coefficient. In this case, the absolute vertical acceleration at the bow and relative vertical motion at a point 0.1 L_{BP} aft of FP are further reduced by 27% and 26% with respect to the parent vessel, respectively. However, the resulting hull form is not practical from the resistance point of view due to the excessive waterplane coefficient.

The final optimization example for the reefer ship is also shown in Table 1 and is denoted as "REEFER OPTIM-2". The constraints imposed in this case are the same as for the previous except for the value of C_{WP}, which is kept constant. As it can be seen from the Table, the optimum hull form is longer, narrower and with LCF shifted considerably forwards. The RMS values for vertical acceleration and relative motion are reduced by 14% and 18% respectively. If this hull form has also reduced resistance characteristics, it might also represent a better alternative for the final product than the parent.

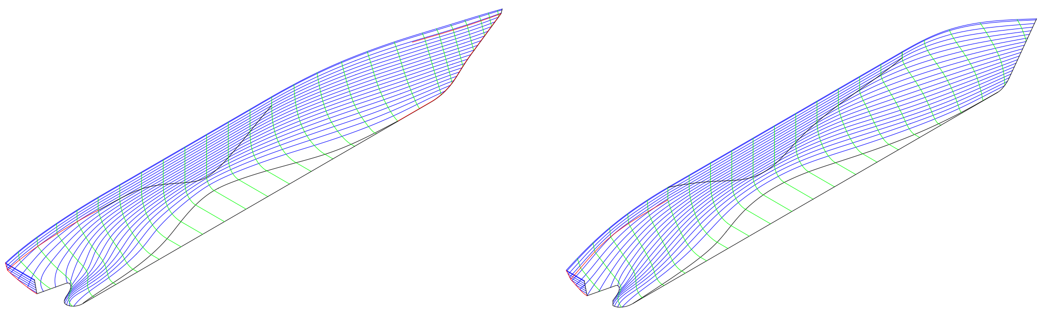

Fig. 2: Isometric views of the parent (left) and the faired optimum hull forms.

In order to experimentally validate the predicted results, two-meter models with the lines of the parent and the faired optimum hull forms have been built and tested in the Towing Tank of NTUA for both resistance and seakeeping. Since the wetted surfaces of the two hull forms are different, the respective EHP(V_S) curves have been plotted in Fig, 3. As it can be seen in this Figure, the EHP requirements of the two hull forms were quite similar with the parent being somewhat better at the higher speeds. Furthermore, both potential flow codes, although they fail to properly estimate the residual resistance, due the lack of the viscous form part of it, they manage to predict correctly the relative merit of wave making resistance of the parent and the optimum, but not optimized for resistance hull form.

The analytical calculations have been carried out at two speeds, 14 and 17 kn, by S-T-F strip theory using the Frank close-fit method and by SWAN2-2002, a modern time-domain 3-D Rankine source panel code. The respective RAO curves for pitch and AVA at a point 0.1 L_{BP} aft of FP, at the lower speed are compared in Fig. 4. According to this figure, both methods reach the same conclusion about the superiority of the faired optimum hull form over the parent one. However, taking into account the respective experimental results (Figs. 7 and 8), it seems that strip theory results are in closer agreement with the experiments than the results derived using a more rigorous 3-D theory, especially in the resonance neighbourhood. On the other hand, additional calculations using extended Lewis-form representations of the sections (the one used in the optimization procedure) led to the conclusion that the method of the 2-D sectional representation affects the results only slightly. Furthermore, the influence of speed in the results is presented in Fig. 5 for the same responses. As it can be deduced from this figure, the superior seakeeping performance of the optimized hull form is preserved at the higher speed, whereas the optimization was done for V_S = 14 knots.

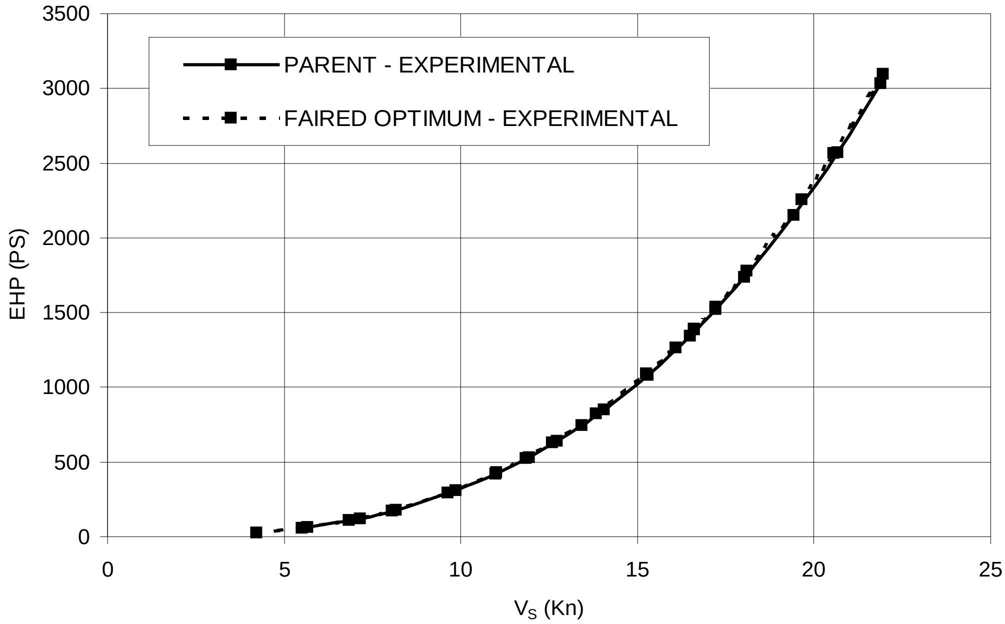

Fig. 3: Effective Horsepower EHP vs. ship speed V_S derived by experiments for the parent and the faired optimum hull forms

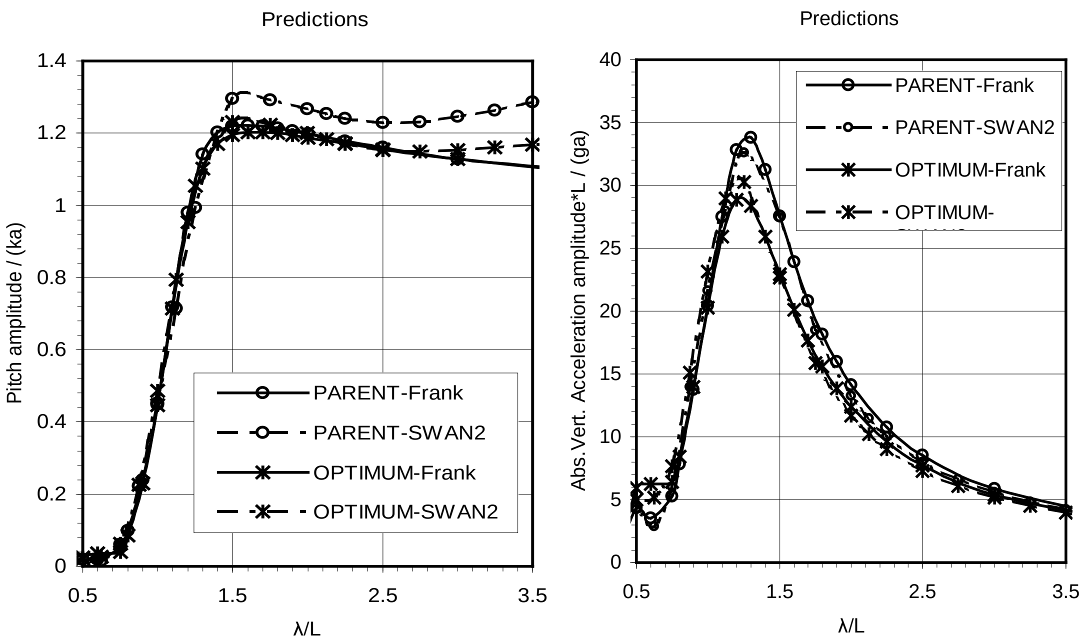

Fig. 4: Predictions using a strip theory (Frank) and a 3-D panel (SWAN2) method for pitch and Absolute Vertical Acceleration in the bow region (0.1 L_{BP} aft of FP) of the parent and the faired optimum reefer hulls (V_S = 14 kn).

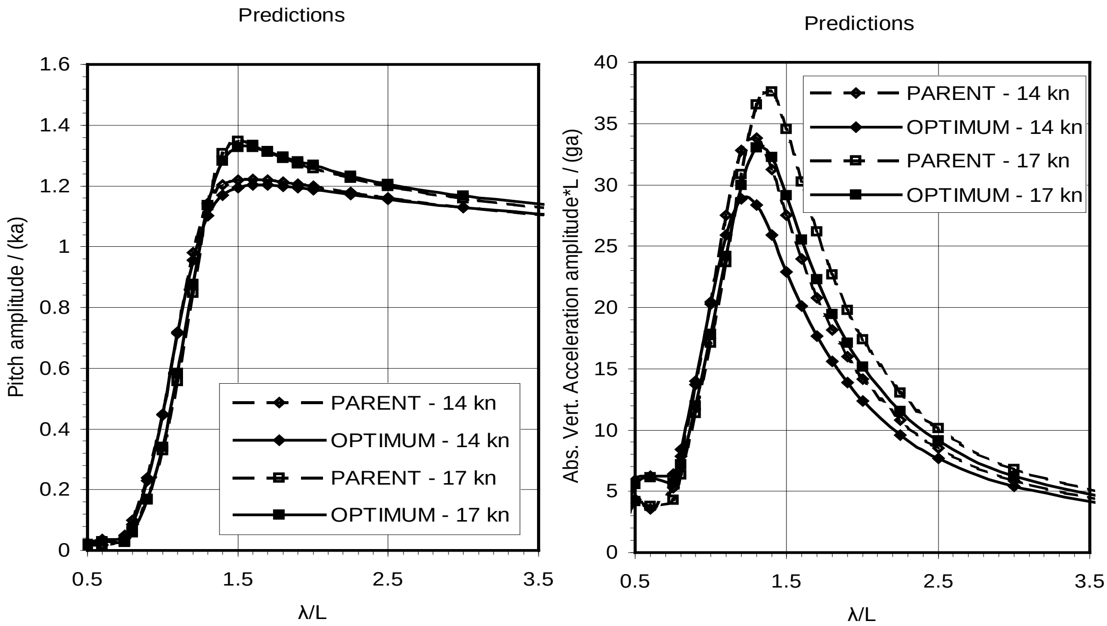

Fig. 5: Predictions using a strip theory method (Frank) and experimental results for pitch and Absolute Vertical Acceleration in the bow region (0.1 L_{BP} aft of FP) of the parent and the faired optimum reefer hulls at speeds V_S = 14 & 17 kn.

The analytical and experimental RAO curves for heave, pitch, AVA and RVM at a point 0.1 L_{BP} aft of FP and added resistance are presented in Figs. 6-10 for ship speed 14 kn. On these figures results, derived by S-T-F strip theory using the Frank close-fit method, are shown. As it can be concluded from these figures, the superior seakeeping performance of the optimized hull form is preserved in all responses.

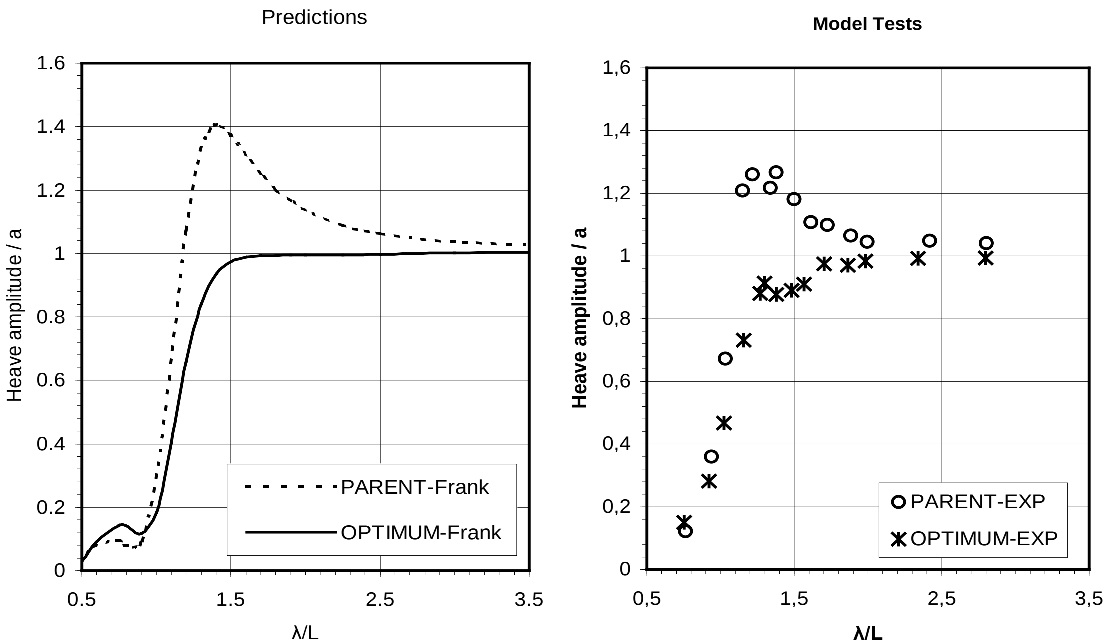

Fig. 6: Heave RAO curve for the parent and the faired optimum reefer hulls (V_S = 14 kn).

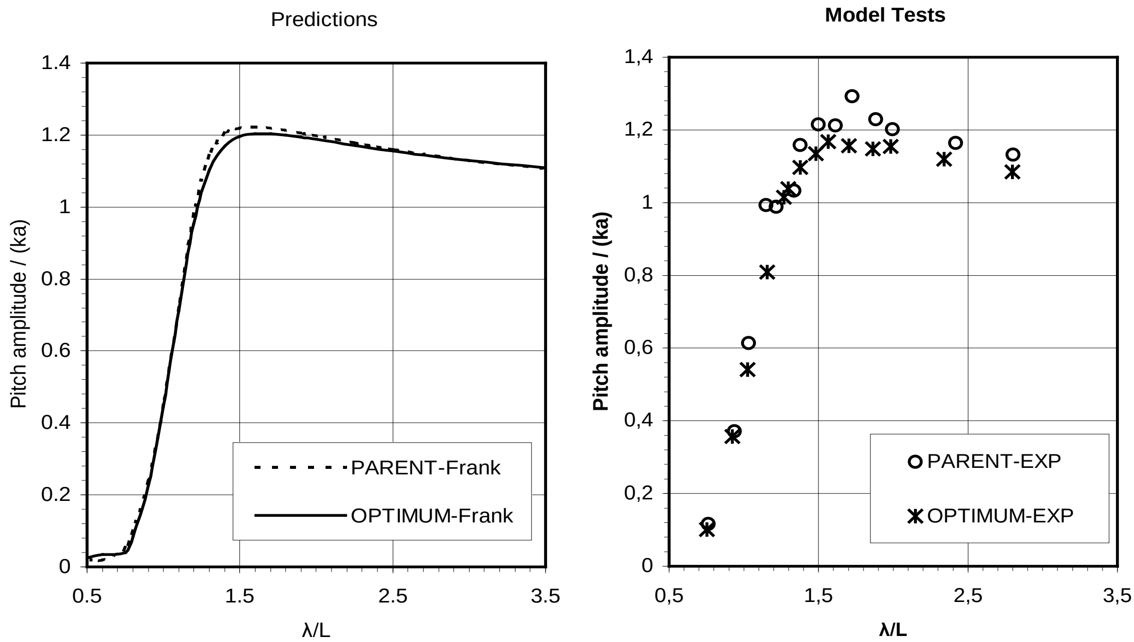

Fig. 7: Pitch RAO curves for the parent and the faired optimum reefer hulls (V_S = 14 kn).

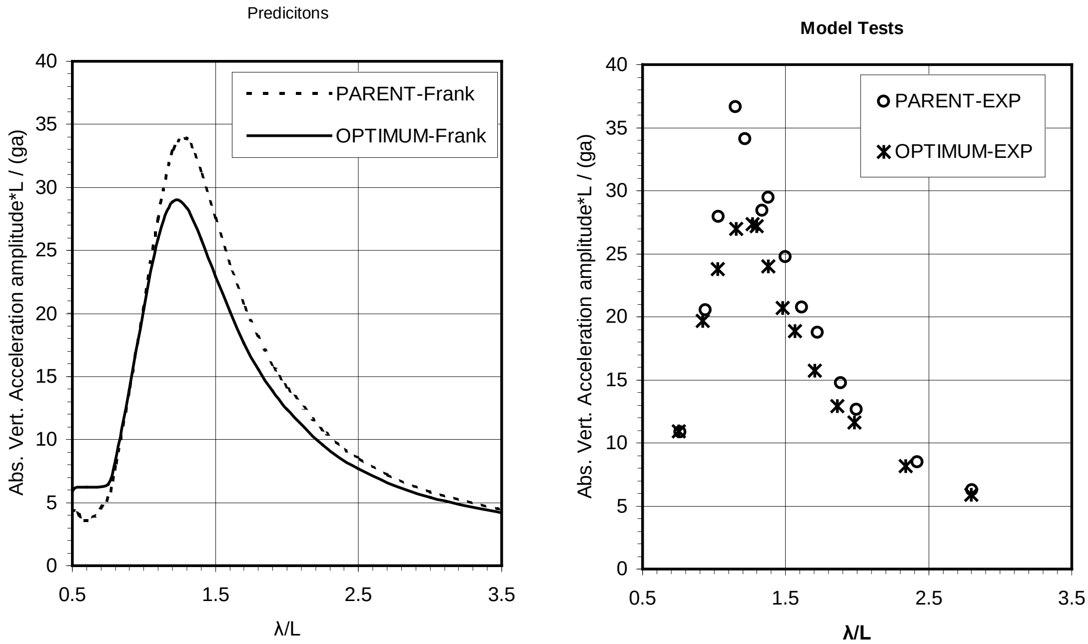

Fig. 8: RAO curve of Absolute Vertical Acceleration in the bow region (0.1 L_{BP} aft of FP) for the parent and the faired optimum reefer hull forms (V_S = 14 kn).

In order to demonstrate the advantages of the optimum hull form in real sea states, the RMS values of the Absolute Vertical Acceleration and the Relative Vertical Motion responses of the parent and the faired optimum hull forms at the aforementioned point per unity $H_{1/3}$ for head (180^o) and bow (135^o) waves at the speed of 14 kn are shown in Figs. 11 and 12, respectively. Mean Added Resistance per unity $H_{1/3}$ for head and bow waves is presented in Fig. 13. As it can be seen in these figures and it can be concluded from similar calculations for beam and following seas, the superiority of the optimized hull form is apparent at all sea states and headings, whereas the optimization was carried out only for head seas. On the same figures the experimental results pertaining to head seas are plotted and one can observe that the predicted differences in seakeeping performance are to a large extent verified experimentally, even though the absolute values of the responses might not be predicted accurately by strip theory calculations, as is in particular true for the relative motion response.

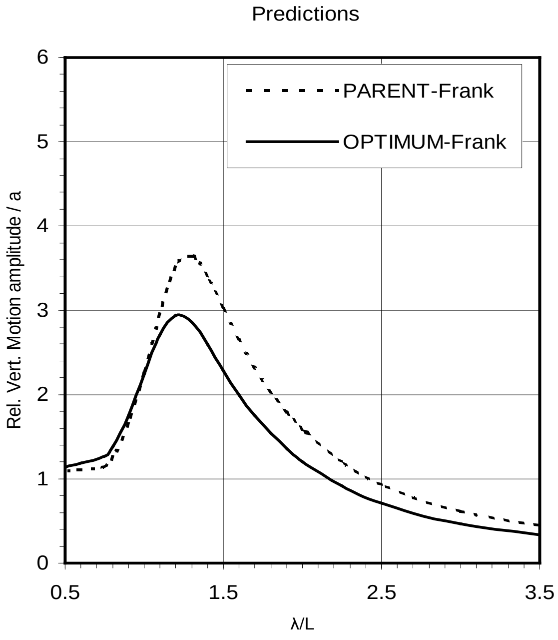

Fig. 9: RAO curve of Relative Vertical Motion in the bow region (0.1 L_{BP} aft of FP) for the parent and the faired optimum reefer hull forms (V_S = 14 kn).

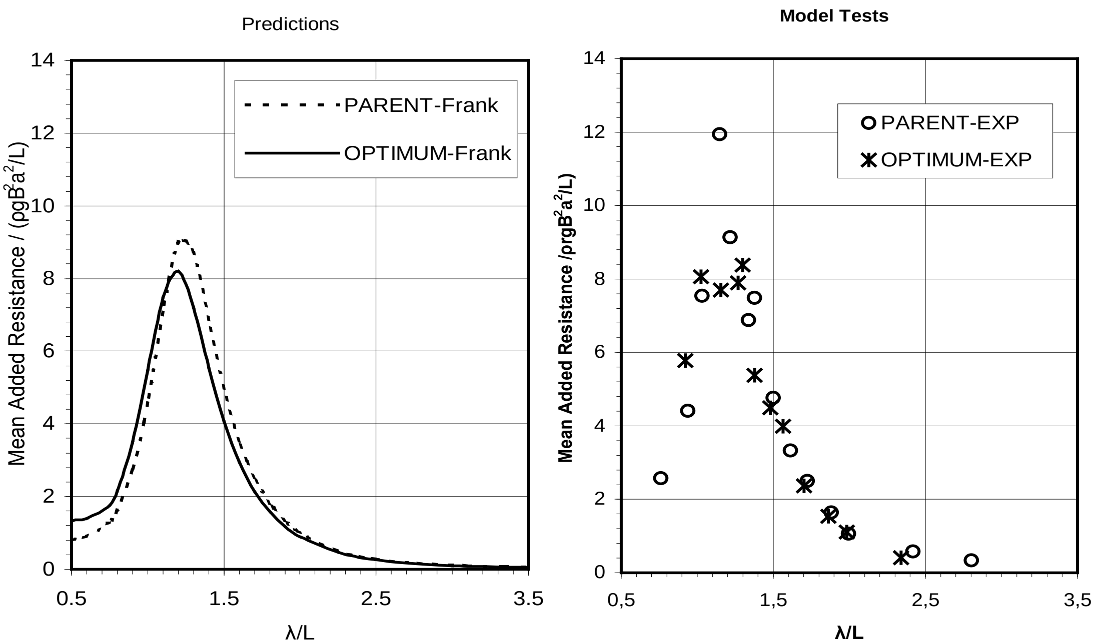

Fig. 10: RAO curve of Added Resistance in waves for the parent and the faired optimum reefer hull forms (V_S = 14 kn).

Bales method could not be used in this case for comparative reasons, since the associated measure of merit, which is based on naval ships, yielded values outside its ordinary range.

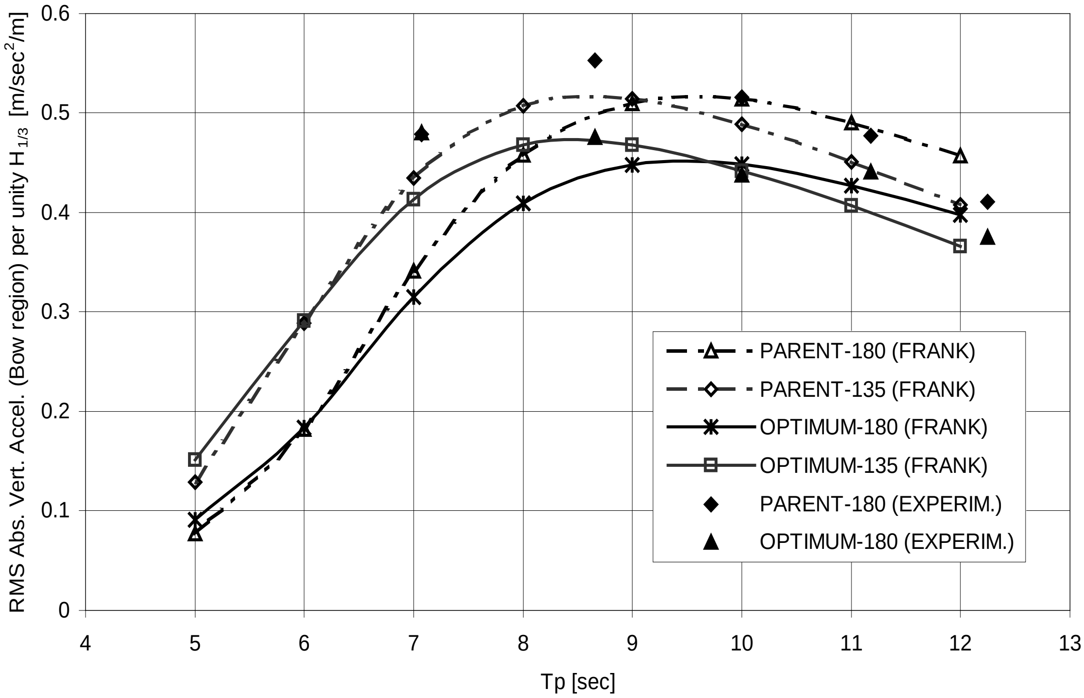

Fig.11: RMS values per unity $H_{1/3}$ of the Abs. Vert. Acceleration (bow region, 0.1 L_{BP} aft of FP) for the parent and the faired optimum reefer hull forms (V_S = 14 kn).

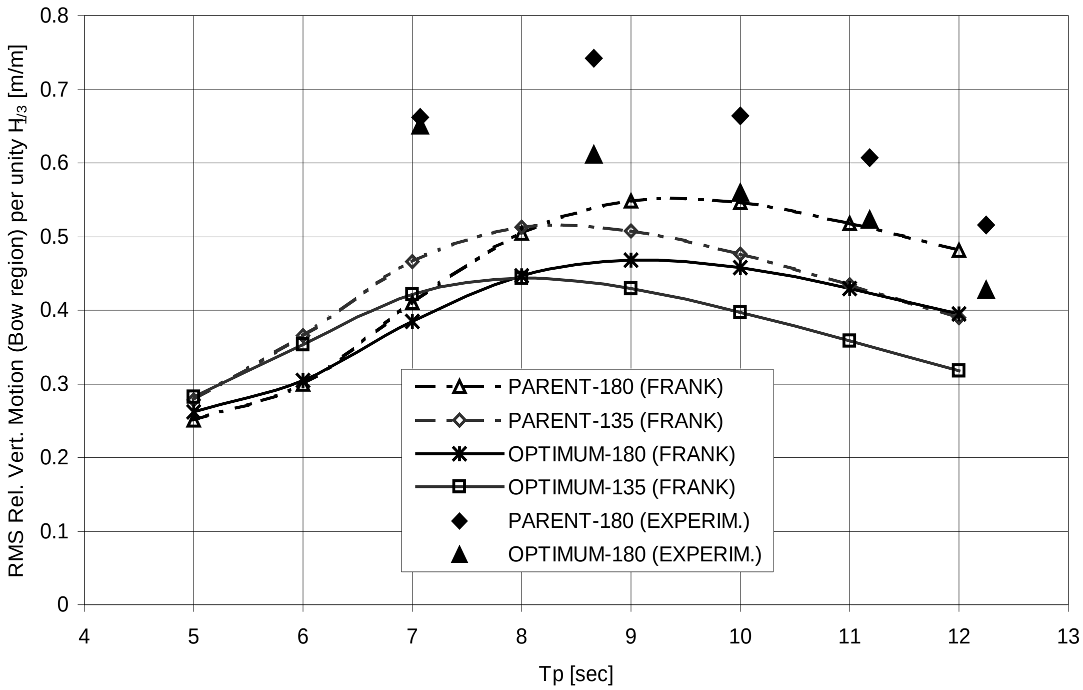

Fig.12: RMS values per unity $H_{1/3}$ of the Relative Vertical Motion (bow region, 0.1 L_{BP} aft of FP) for the parent and the faired optimum reefer hull forms (V_S = 14 kn).

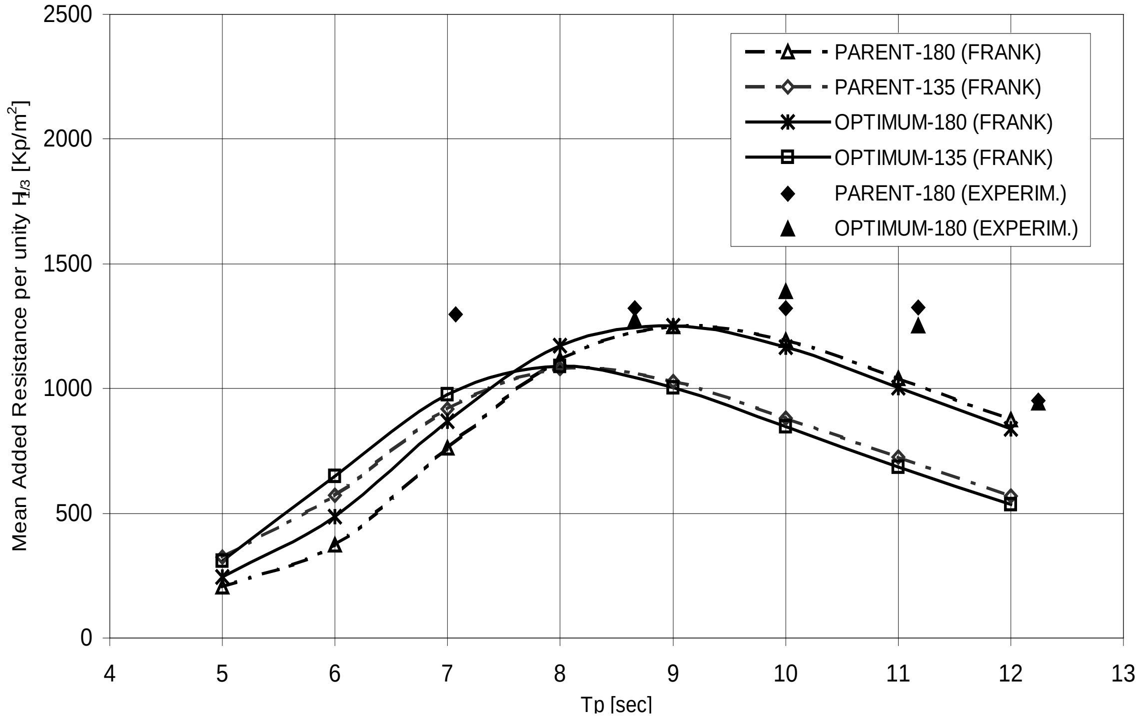

Fig.13: Mean Added Resistance per unity $H_{1/3}$ for the parent and the faired optimum reefer hull forms (V_S = 14 kn).

4.2 The Destroyer Case

The second application case of the proposed method is recent and was performed on the US Navy ship DDG 51. Models scaled by 1:24.824 of that vessel have been constructed and tested by DTMB (model DTMB 5415) and INSEAN (model C.2340, Campana and Peri, 2000). The body plan of the parent vessel is shown in Fig. 14.

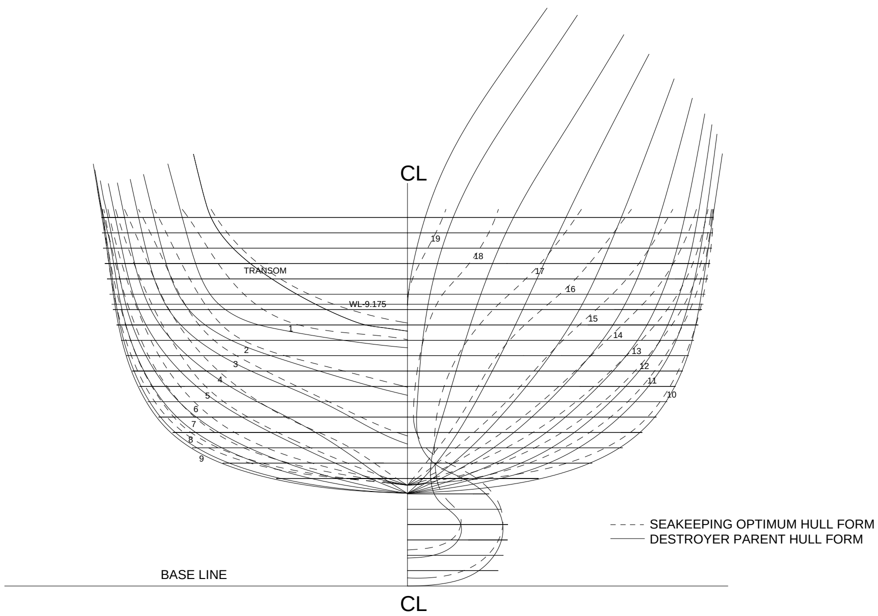

Fig. 14: Body plan of the parent and the seakeeping optimum destroyer hull form

The secondary hull form parameters of the hull form were optimized for the bow AVA and RVM at a speed corresponding to Fn = 0.41. The optimization procedure recommended the following modifications to be carried out (in parentheses the range of the exploration region):

δC_{WP} = +4.00% (±4.00%), δLCB = -0.125% L_{WL} (±4.00%)
LCF = +3.50% L_{WL} (±3.50%), KB = -2.00% (±2.00%)

The main characteristics of the parent and the optimized hull forms are shown in Tables 2a and 2b. Both the parent and the optimum hull forms have been faired using TRIBON M2 system. A model of the optimized hull form, denoted as Ag has been constructed and tested by QINETIQ within the EUCLID 10.14 project (Watson et al, 2002).

Table 2a

Main geometrical characteristics of DDG-51 destroyer

Length of waterline	L_{WL} (m)	142.00
Beam	B (m)	18.90
Breadth	T (m)	6.16
Displacement	Δ (t)	8636.00
Block coefficient	C_B	0.502
Wetted surface	WS (m^2)	2949.50

Table 2b

Characteristics of the parent, the optimum and the final destroyer hull form.
(The volume of displacement is 6103 m^3 and the draft 6.50 m in all cases.)

CASE	WS [m^2]	C_M	C_{WP}	LCB [%L_{BP}]	LCF [%L_{BP}]	KB [m]
DESTROYER PARENT	2949.5	0.825	0.778	-0.591	-4.867	3.691
DESTROYER OPTIMUM (Ag)	2967.2	0.827	0.777	0.084	-2.655	3.584
DESTROYER FINAL HULL FORM	2999.2	0.798	0.780	-0.147	-2.777	3.668

The experimentally derived EHP requirements in calm water are presented in Fig. 15. As it can be seen in this Figure, the required EHP of the optimized for seakeeping hull form is very similar to that of the parent one, at the design speed corresponding to Fn = 0.41, and slightly higher at lower speeds. Similar trends are analytically predicted (using both SWAN2 and SHIPFLOW codes), although both codes predict C_W coefficients significantly lower than the measured C_R coefficients.

In the sequel, using the optimum hull form as parent, a stern wedge was fitted on the model and some minor modifications in the bow region to remedy some flow irregularities have been carried out and additional fairing has been applied, leading to a final hull form with resistance reduced by 6.4% at the service speed corresponding to Fn = 0.41, according to SWAN2. However, the latter hull form has only analytically been assessed.

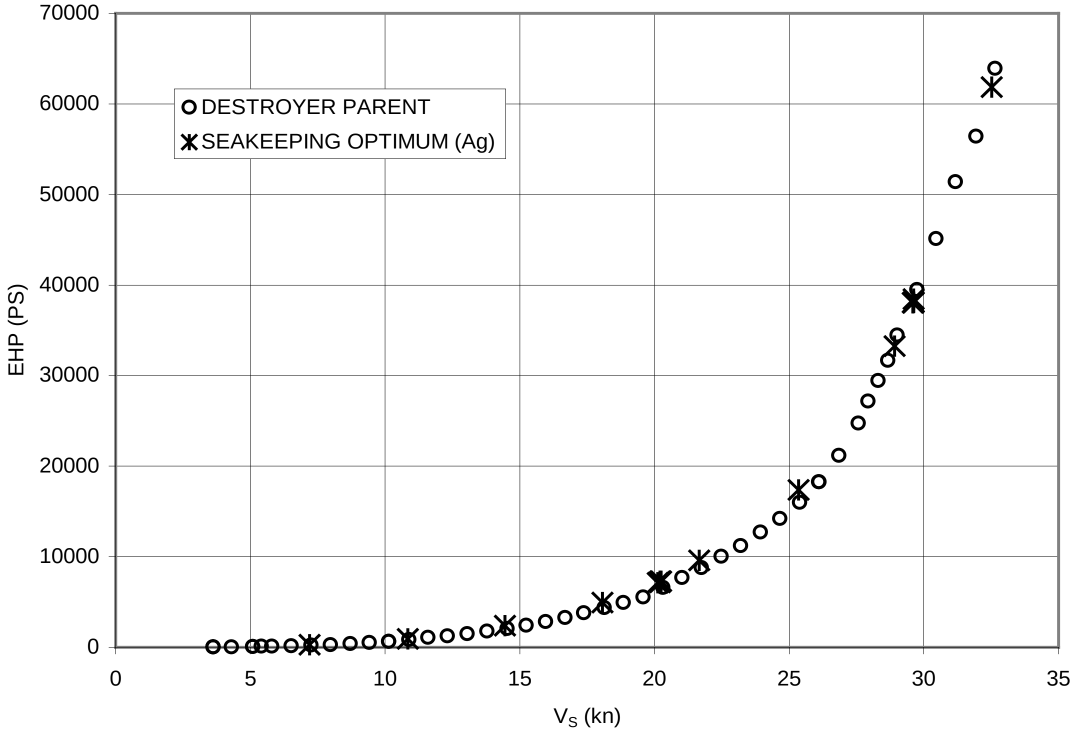

Fig.15: Experimentally derived EHP (VS) requirements for the parent and the seakeeping optimum destroyer hull forms.

The respective RAO curves of the dynamic responses, i.e. heave, pitch, AVA and RVM at a point 0.1 L_{BP} aft of FP, and added resistance for the three hull forms (the parent, the seakeeping optimum Ag hull form and the final hull form derived by optimizing Ag hull form for resistance) are shown in Figs. 16-20. In these figures analytically derived results using NTUA strip theory code and Frank close-fit method to model the sectional characteristics and SWAN-2 time-domain panel-method code are presented. A careful inspection of these figures leads to the following comments:

- The overall superiority of the optimized hull form is demonstrated experimentally.
- Both analytical tools predict satisfactorily the superiority of Ag hull form over the parent one for seakeeping.
- Contrary to strip theory, SWAN-2 over-predicts the peak heave response. Heave is not a very significant response. However, it has been included among the responses considered within EUCLID project.
- Both codes provide in general reliable AVA predictions. However strip theory is by far superior in the prediction of the relative merit of the optimized hull form compare to the parent one.
- The seakeeping optimized hull form is superior also with respect to added resistance.

On the basis of the optimization results, it can again be concluded that increasing C_W, moving LCB and LCF forwards and lowering VCB reduce the peak values of the RAO of vertical acceleration at FP by 18% on the basis of experimental values. It should be mentioned here that, the experimental RAO curves have been based on model tests in random waves of a specific spectrum.

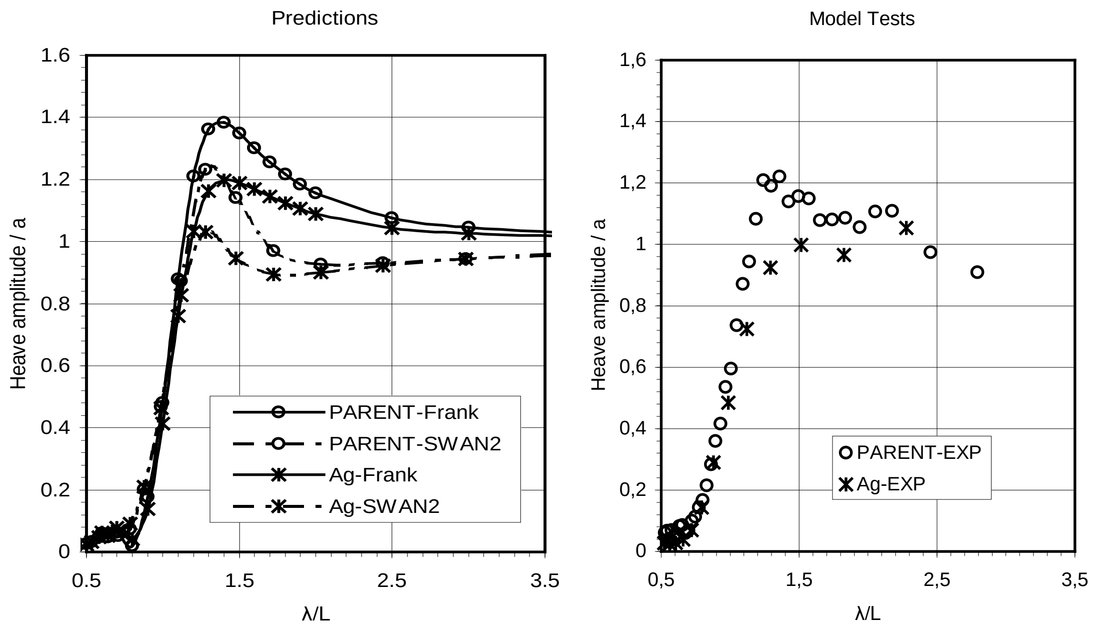

Fig.16: Analytical and experimental results for the heave RAO curve of the parent and the seakeeping optimum destroyer-type hull forms (Fr. No. = 0.41).

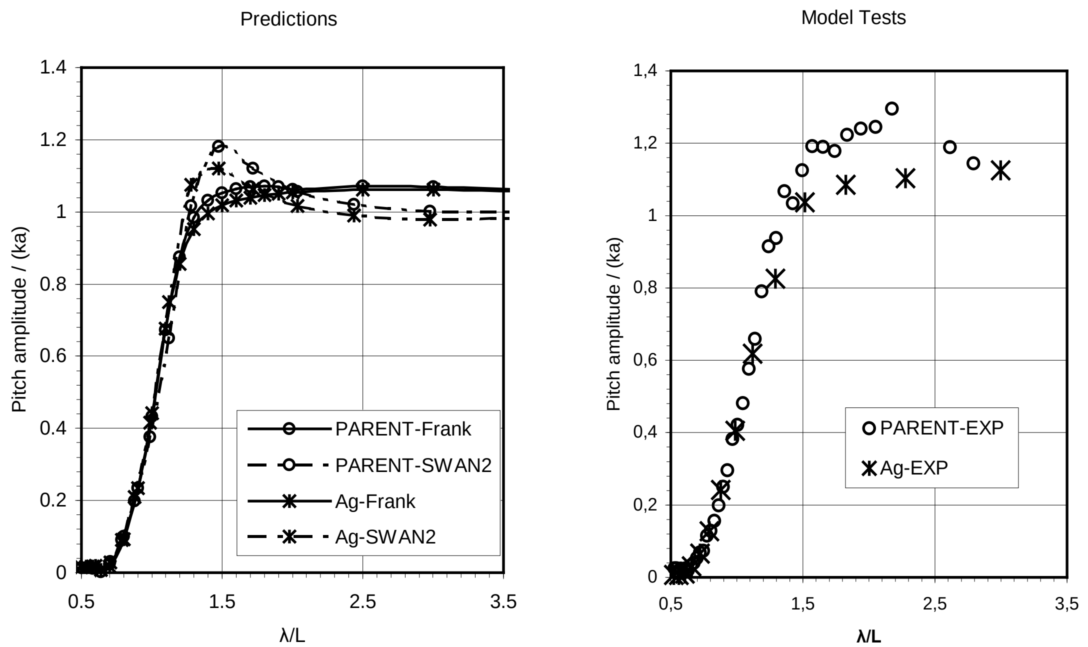

Fig.17: Analytical and experimental results for the pitch RAO curve of the parent and the seakeeping optimum destroyer-type hull forms (Fr. No. = 0.41).

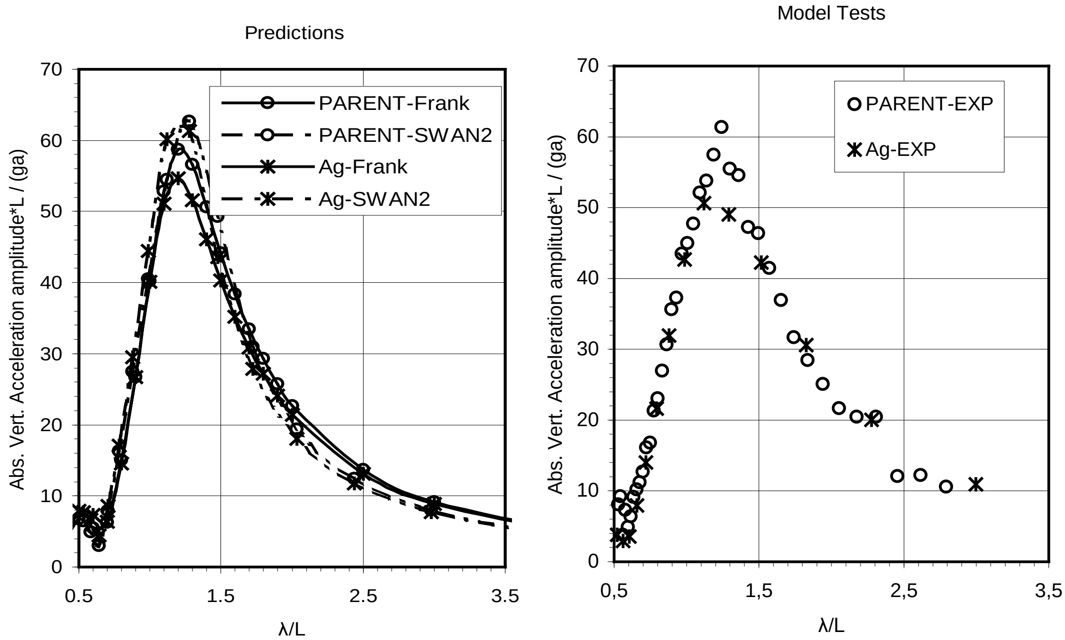

Fig.18: Analytical and experimental results for the RAO curve of bow AVA of the parent and the seakeeping optimum destroyer-type hull forms (Fr. No. = 0.41).

Calculations have been carried out also for the final hull form, which was derived by applying a non-automatic procedure of local (minor) modifications to reduce cal water resistance. The AVA peak response at a point 0.1 L_{BP} aft of FP for that vessel was found to be reduced by 3.8% compared to that of the seakeeping optimum (Ag) hull form, according to SWAN-2 code. However, both strip theory and SWAN2 codes fail to distinguish between the seakeeping optimum hull form and the final one (the respective response curves are overlapping). Thus, the respective results are not given in the Figures 16-20.

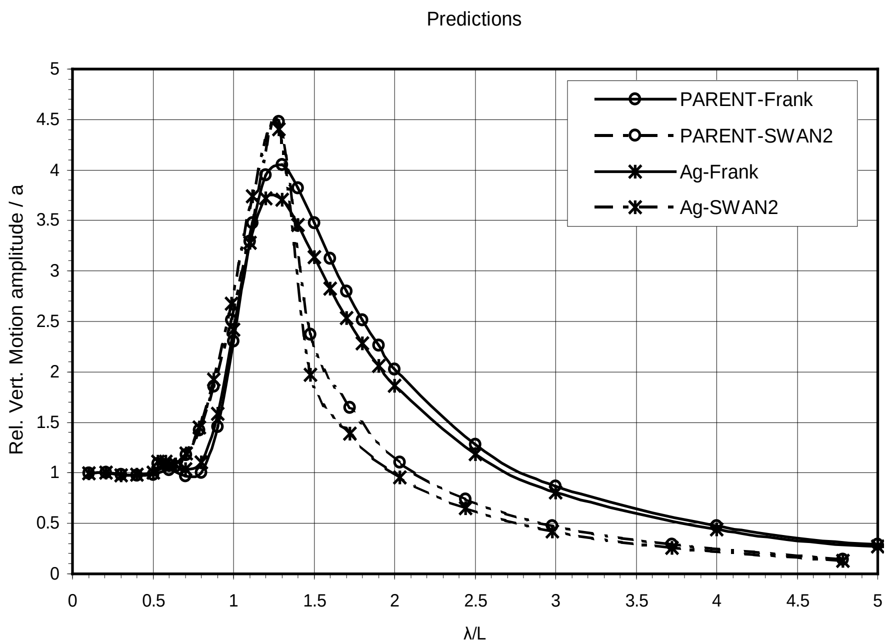

Fig.19: Analytical results for the RAO curve of bow RVM of the parent and the seakeeping optimum destroyer-type hull forms (Fr. No. = 0.41).

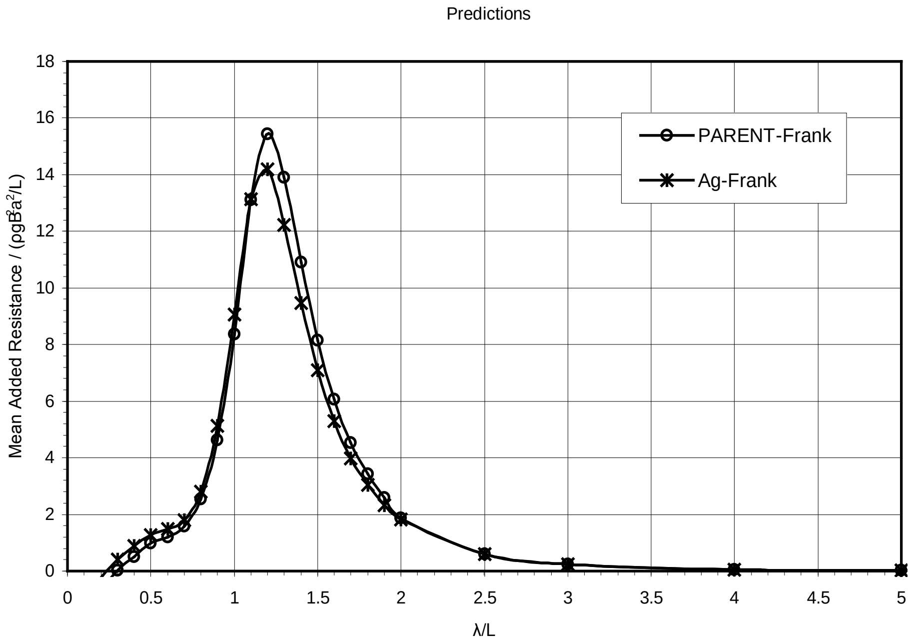

Fig.20: Analytical results for the RAO curve of added resistance in head waves of the parent and the seakeeping optimum destroyer-type hull forms (Fr. No. = 0.41).

Finally, Bales method, which has been based on a database of destroyer-type hull forms, provides consistent estimates for the seakeeping merits of the parent hull form (R = 8.71), the optimized for seakeeping hull form (R = 9.75) and the final one (R = 9.87).

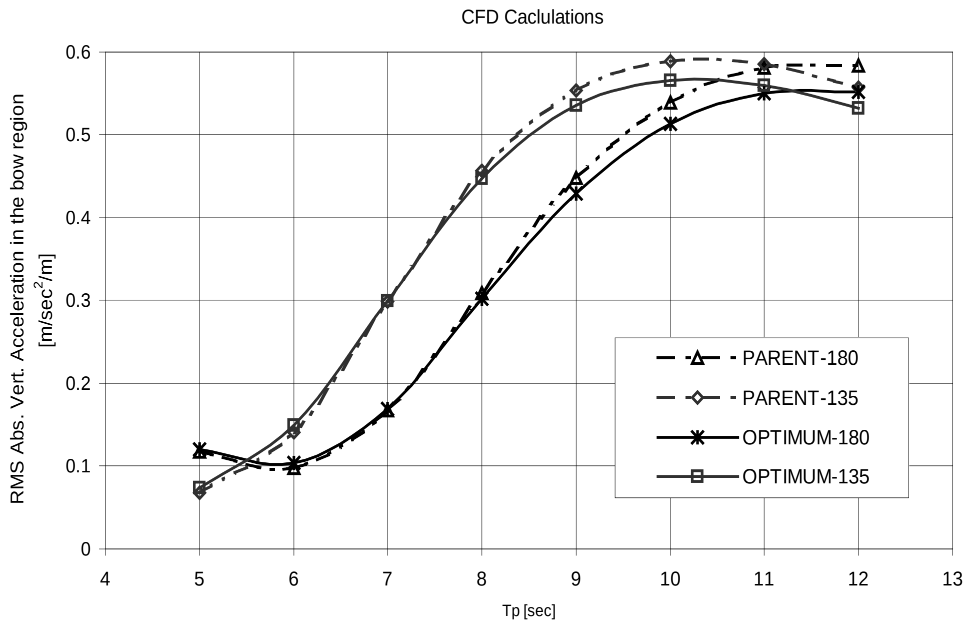

Fig.21: RMS values per unity $H_{1/3}$ of the Abs. Vertical Acceleration in the bow region (0.1 L_{BP} aft of FP), for the parent and the seakeeping optimum destroyer-type hull forms (Fn = 0.41).

In order to demonstrate the advantages of the optimum hull form in real sea states, the RMS values of the Absolute Vertical Acceleration and the Relative Vertical Motion response at the aforementioned point per unity $H_{1/3}$ for head (180°) and bow (135°) waves are depicted in Figs. 21 and 22, respectively. Additional calculations have been carried out for the rest of the heading angles. Mean Added Resistance per unity $H_{1/3}$ for the above heading angles is presented in Fig. 23. The standard strip theory code of NTUA (SPP-86) using Frank method was used for these calculations, too. As it can be seen in these figures and concluded from the additional calculations, the superiority of the optimized hull form is apparent at the longer modal periods, corresponding to severe seas, and all headings, whereas the optimization was carried out for head seas.

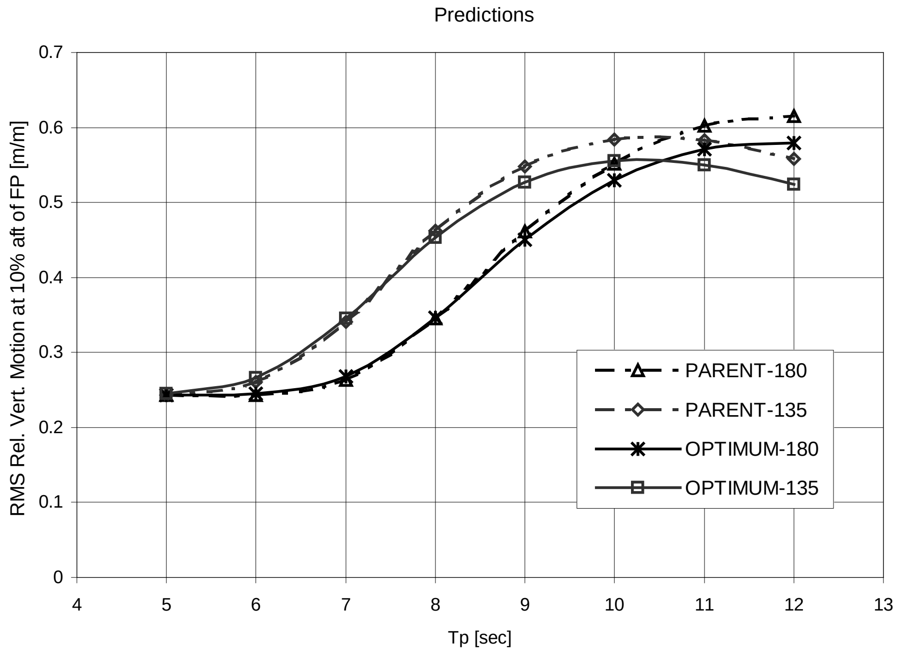

Fig.22: RMS values per unity $H_{1/3}$ of the Relative Vertical Motion in the bow region (0.1 L_{BP} aft of FP) for the parent and the seakeeping optimum destroyer-type hull forms (Fn = 0.41).

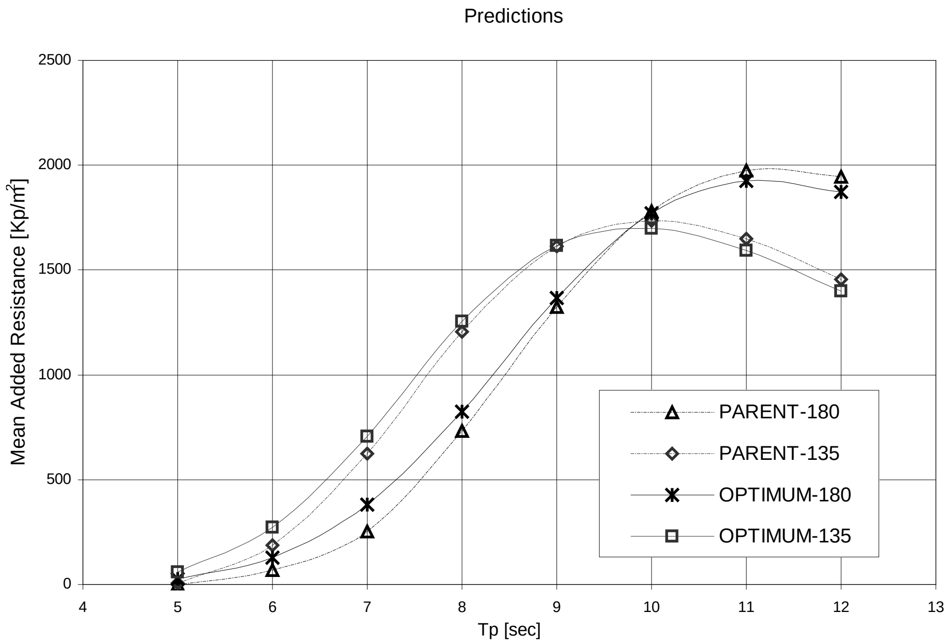

Fig.23: Mean Added Resistance per unity $H_{1/3}$ for the parent and the seakeeping optimum destroyer-type hull forms (Fn = 0.41).

5. DISCUSSION AND CONCLUSIONS

In this paper a method for seakeeping optimization of hull forms is described and evaluated. The main advantages of the proposed method can be summarized as follows:

a. The use of the three-parameter Lewis-form representation of the ship sections allows the desirability of U forms or V form to be investigated.
b. The method is suitable for immediate incorporation in the preliminary design spiral and it can readily accommodate all necessary design constraints.
c. The method is efficiently executed on a PC as it circumvents the need of computing both the full RAO and the performance at sea for all hull form variants.
d. The method directly evaluates the performance of the parent and the variant hull forms and carries out optimization in a comparative sense on the basis of regular wave responses. Thus, the optimisation procedure is not affected by the empirically imposed seakeeping operability criteria, whose satisfaction can only be assessed a posteriori in both an absolute and a comparative sense.
e. Resistance, or rather propulsion optimization, can be carried out afterwards, without affecting significantly the superior seakeeping qualities of the seakeeping optimum hull form.

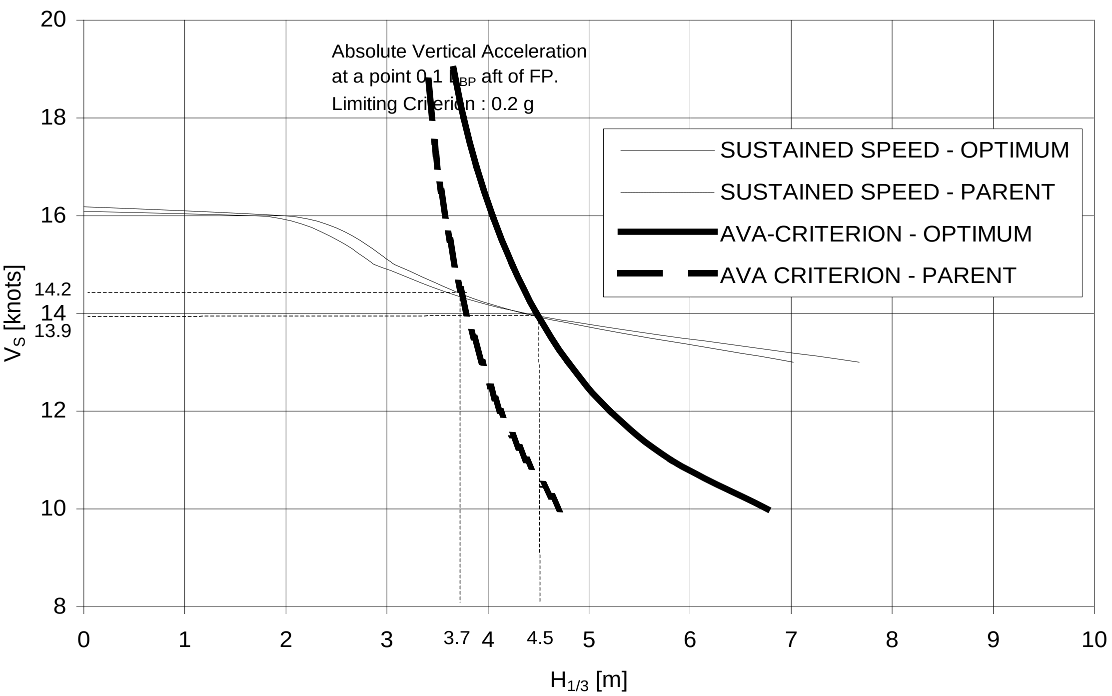

Fig.24: Powering Diagram in fully developed head seas. Involuntary speed loss and limiting speed for the parent and the seakeeping optimum reefer hull forms.

The method is complemented by the suggestion that the final assessment of seakeeping performance should be expressed in terms of the sustained ship speed in various sea conditions up to those limiting the operability of the vessel. To illustrate this, the powering diagrams of both the parent and the optimum hull form of the reefer ship are shown in Fig. 24. The involuntary speed reduction curves are computed by taking into account the added resistance in waves and computing the maximum attainable ship speed on the basis of the engine and propeller characteristics (assumed to be the same for both ships in this case). From these curves it can be concluded that the reduced added resistance of the optimum ship compensates in the higher sea states for her slightly higher calm water resistance. The voluntary speed reduction curves, which complement the powering diagram, indicate that the RMS value of the vertical acceleration in the bow region (0.1 L_{BP} aft of FP) has reached the predetermined limit of 0.2g. The combined involuntary-voluntary speed reduction curve determines the region of operation of the vessel at sea and therefore it describes the capability of the vessel to fulfil its transport mission economically. The expanded region of operation of the optimized vessel is a very strong indication of the effect of good seakeeping characteristics on overall ship performance.

Returning now to the optimization examples, it can be stated that the most obvious changes in hull form geometry, which are beneficial to seakeeping, are the increase of the waterplane area and the shifting of its centre of area forwards. As these changes are usually accompanied by an increase in ship resistance, one has to be careful in specifying the amount of permissible changes in the values of these parameters. More generally, an experienced Naval Architect should specify all constraints, since the computer alone cannot do creative ship design.

All optimization examples were performed with respect to vertical motions only. This is adequate because lateral motions and especially roll, can be treated by bilge keel design, rudder and skeg design, anti-rolling devices, modification of GM etc.

Finally, it seems that the optimization procedure, which avoids the lengthy operability calculations for the encountered sea states, is rather insensitive to ship speed and/or heading, at least for conventional displacement hull forms. That is that the optimized hull form for one speed and heading retains its superiority for other speeds and headings. This statement demonstrated in Figs. 5, 11 and 21 for AVA in the bow region, greatly reduces the computation effort.

On the basis of the above it can be concluded that the inclusion of the seakeeping performance in ship design is both desirable and possible by the use of the method presented herein.

NOMENCLATURE

a	wave amplitude
AVA	Absolute Vertical Acceleration
B	ship's breadth
B(x)	waterline curve B(x)
BM	metacentric radius
C_B	block coefficient
C_F	$= R_F / (\frac{1}{2} \rho WS \cdot V^2)$, residuary resistance coefficient
C.G.	centre of gravity
C_M	midship section coefficient
C_P	horizontal prismatic coefficient

C_R $= R_R / (\frac{1}{2}\rho WS \cdot V^2)$, residuary resistance coefficient
C_{VP} vertical prismatic coefficient
C_W $= R_W / (\frac{1}{2}\rho WS \cdot V^2)$, wave resistance coefficient
C_{WP} waterplane area coefficient
EHP Effective Horsepower
Fn $= V / \sqrt{gL_{WL}}$, Froude number
FP forward perpendicular
GM metacentric height
k $= 2\pi/\lambda$, wave number
KB vertical distance of the centre of buoyancy from keel
KB(x) longitudinal distribution of the vertical position of the centroid of ship sections above the keel
KG vertical distance of the centre of gravity from keel
L waterline length
L_{BP} length between perpendiculars
LCB longitudinal position of Centre of Buoyancy (positive forward amidships)
LCF longitudinal position of Centre of Flotation (positive forward amidships)
LCG longitudinal position of Centre of Gravity (positive forward amidships)
L_{WL} waterline length
R Bales' seakeeping rank factor
R_F frictional resistance
R_R residuary resistance
R_T total resistance
RVM Relative Vertical Motion
R_W wave resistance
S(x) sectional area curve
SHP Shaft Horsepower
T mean draught
t trim (positive by stern)
V speed
VCB vertical centre of buoyancy
WS wetted surface at rest
Z(x) longitudinal profile curve
Δ displacement
λ wave length
ρ water density
∇ Volume of displacement

6. ACKNOWLEDGEMENTS

The author would like to acknowledge HULLOPT (Optimal Techniques for Hull Geometry), EUCLID 10.14 Project sponsored by CEPA 10, for supporting this research and for permitting the publication of the results regarding DDG 51 and Ag hull. Greece, Italy, Turkey and United Kingdom participated in this project with industrial partners NTUA, INSEAN and FINCANTIERI, ITU and QINETIQ, respectively. He also would like to thank Prof. T. Loukakis, the supervisor of his PhD Thesis, who read this manuscript and provided valuable comments and Mr D. Chalkias for accomplishing some of the tedious analytical calculations.

7. REFERENCES

1. Athanassoulis G.A. & Loukakis T.A. (1985). An Extended-Lewis Form Family of Ship Sections and Its Applications to Seakeeping Calculations, *Intl. Shipbuilding Progress*, Vol. 32, No.366, pp.33-43.
2. AUTOSHIP System Corporation, AUTOSHIP 7.1, User Manual, Vancouver, Canada, 1999.
3. Bailey, P.A., Hudson, D.A., Price, W.G. and Temarel, P. (2000). Comparisons between Theory and Experiment in a Seakeeping Validation Study, Trans. RINA, Vol. 142, pp. 44-77.
4. Bales N.K. (1980). Optimizing the Seakeeping Performance of Destroyer-Type Hulls, 13th ONR Symposium on Naval Hydrodynamics, Tokyo, Japan.
5. Blok, J.J. and Beukelman, W. (1984), The High-Speed Displacement Ship Systematic Series Hull Forms – Seakeeping Characteristics, Trans. SNAME, Vol. 92, pp. 125-150.
6. Bloor, M.I.G. and Wilson, M.J. (1999), Parametric Geometry and Optimization of Hull Forms, 10th Intl. Conf. On Computer Application In Shipbuilding, MIT, Cambridge, USA, June 7-11.
7. Blume, P. and Kracht, A. (1985), Prediction of the Behavior of Propulsive Performance of Ships with Bulbous Bow in Waves, Trans. SNAME, Vol. 93, pp. 79-94.
8. Bruzzone, D. Gualeni, P. and Sebastiani, L. (2000), Application of Green's Function Methods to the Seakeeping Computations for High-Speed Vehicles, Intl. Conf. On Ship and Shipping Research NAV 2000, Paper 9.1, Venice, September 19-22.
9. Campana, E.F. and Peri, D. (2000). Progress Report for EWP1 Technical Report for EWP2 of HULLOPT, EUCLID Project RPT 10.14/003 (Optimal Techniques for Hull Geometry), Vers. 2, INSEAN, Italy, January.
10. Frank, W. (1967). Oscillation of Cylinders in or Below the Free Surface of Deep Fluids, NSRDC, Rep. No. 2375, Washington, D.C.
11. Grigoropoulos G.J. and Loukakis T.A. (1988). A New Method for Developing Hull Forms with Superior Seakeeping Qualities. CADMO'88. Southampton, U.K, September.
12. Grigoropoulos G.J. (1989). Hull Form Optimization with Respect to Seakeeping, PhD Thesis, NTUA, Dept. of Naval Arch. and Marine Eng., Athens, Greece, May.
13. Grigoropoulos, G.J., Loukakis, T.A. and Perakis, A.N. (2000). Seakeeping Standard Series for Oblique Seas (A synopsis), *Ocean Engineering Journal*, Vol. 27, pp. 111-126.
14. Grossi, L., Brizzolara, S., Caprino G. and Sebastiani, L. (1998) Seakeeping Design of Fast Monohull Ferries, Proc. 7th Intl. Symp. On Practical Design of Ships and Mobile Units PRADS '98, The Hague, The Netherlands, September 1998, ed. by M.C.W. Oosterveld and S.G. Tan, Elsevier Science B.V, pp.613-624.
15. Grossi, L. and Dogliani, M. (2000) Load and Seakeeping Assessment of HSC Based on Full-Scale Monitoring, Intl. Conf. On Ship and Shipping Research NAV 2000, Paper 2.8, Venice, September 19-22.
16. Harries, S. (1998) Parametric Design and Hydrodynamic Optimization of Ship Hull Forms', Ph.D. Thesis, Inst. for Ship and Sea Technology Tech. Univ. of Berlin, Mensch and Buch Verlag, September.
17. Hearn, G.E., Hills, W. and Sarioz, K. (1992), Practical Seakeeping for Design: A Ship Shape Approach, Trans. RINA, Vol. 134, Part B, pp. 215-234.

18. Hooke R. & Jeeves T.A. (1961). Direct Search Solution of Numerical and Statistical Problems, Journal of Assoc. for Computing Machinery, Vol.8, No.4, p. 212
19. Kockums (2002), TRIBON M2, User Manual, Cambridge MA 02138, USA.
20. Korvin-Kroukovsky, B.V.(1955). Investigation of Ship Motions in Regular Waves. Trans. SNAME, Vol. 63
21. Kring, D. and Sclavounos, P. (1995). Numerical Stability Analysis for Time-Domain Ship Motion Simulations. Journal of Ship Research, Vol. 39, No. 4, pp. 313-320.
22. Lackenby H. (1950). On the Systematic Geometrical Variation of Ship Forms, Trans. INA, Vol. 92, p. 289.
23. Pigounakis, K.G. (1997), Fairing Methods of Planar and Space Curves under Design Constraints – Applications in Computer-Aided Ship Design, PhD Thesis, Dept. of N.A. & M.E., Nat. Techn. Univ. of Athens, Greece, February.
24. Salvesen N., Tuck E.O. and Faltinsen O. (1970). Ship Motions and Sea Loads, Trans. SNAME, Vol. 78, pp. 250-287.
25. SHIPFLOW Users Manual, Revision 2.4, 1999 FLOWTECH, Gothenburg, Sweden, June 1999.
26. SPP-86 (1986). User Manual, Lab. for Ship and Marine Hydrodynamics, National Technical Univ. of Athens, Athens, Greece.
27. SWAN2 (2002). User Manual. Ship Flow Simulation in Calm Water and in Waves, Boston Marine Consulting Inc., Boston MA 02116, USA.
28. Valkhof, H.H., Hoekstra, M. and Andersen, J.E. (1998). Model Tests and CFD in Hull Form Optimization, Trans. SNAME, Vol. 106, pp. 391-412.
29. Walden, D.A., Kopp, P.J and Grundmann, P. (1985). Optimization of Hull Form for Seakeeping and Resistance, MARIN Workshop on Developments in Hull Form Design, Wageningen, October.
30. Wangdahl G.E. (1972). The External Penalty Function Optimization Technique and Its Application to Ship Design, The Univ. of Michigan, Ann Arbor, Rep. No.129.
31. Watson, S.J.P., Richardsen, C. and Johnson, M.C. (2002). Technical Report for EWP2 of HULLOPT, EUCLID Project RPT 10.14/003 (Optimal Techniques for Hull Geometry), Vers. 0, QINETIQ, UK, February.