Hydrodynamic Fine-Tuning of a Pentamaran for High-Speed Sea Transportation Services

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ABSTRACT

This paper discusses the hydrodynamic optimization of the central hull of a 290m Pentamaran for SeaBridge *in order to maximize the speed of the vessel with a pre-determined machinery package. The optimization of the central hull was performed by combining the parametric CAD program* FRIENDSHIP-Modeler *with the CFD code* SHIPFLOW *via the generic optimization tool* FRIENDSHIP-Optimizer. *A scale model of the optimized central hull was made and a series of resistance tests undertaken to verify the accuracy of the CFD calculations and to prove the validity of the optimization.*

Figure 1: *Rendering of the* SeaBridge *Pentamaran*

INTRODUCTION

The vessel is a 290m, 6500t Dwt high speed Pentamaran Ro-Pax vessel designed for SeaBridge International Inc. The vessel is powered by a Diesel Electric Propulsion plant in combination with waterjets. A rendering of the vessel is shown in Figure 1.

The *SeaBridge* approach uses the sea to complement existing land-based travel on selected routes to attract freight movements away from overcrowded highways, for at least part of the journey from shipper to receiver. By using the sea as a bridge, *SeaBridge* intends to transport more goods, with less environmental impact, at lower cost, and in a shorter time frame than any comparable transportation alternative available today.

Sea transport at 40 knots and higher requires the utmost effort to reduce energy consumption. The work presented in this paper is, therefore, dedicated to the systematic fine-tuning of the Pentamaran's central hull. The volume, position and shape of the sidehulls were not considered as part of this study, since they had been subject to previous investigations in which a favourable method for designing the sidehull configuration had already been established.

For the central hull, formal strategies to improve the calm water hydrodynamic performance were employed. A sophisticated parametric definition of the hull shape was established within the Computer Aided Design (CAD) tool *FRIENDSHIP-Modeler* for an efficient and effective form optimization.

The repeating stages of geometric modelling, hydrodynamic simulation, performance assessment and systematic variation were integrated into a

Computer Aided Engineering (CAE) environment utilizing the *FRIENDSHIP-Optimizer*. A set of important hull form parameters were identified for the optimization task. Important equality and inequality constraints were monitored – for instance, the displacement was kept constant while the longitudinal center of buoyancy was limited to a practical range. Several hundred design alternatives were automatically generated and numerically analyzed using the Computational Fluid Dynamics (CFD) tool *SHIPFLOW*. This served to draw a comprehensive picture of the search domain and to identify the most promising design alternatives.

Finally, a model resistance test program was undertaken in order to confirm the validity of the results obtained through CFD. These results have shown that the hydrodynamic optimization via CFD is a powerful method for the fine-tuning of hull lines, even though there were difficult flow phenomena about the stern region.

In the sections to come we will first elaborate on the vessel and its mission. We will then discuss the parametric modelling of the central hull and show exemplary form variations to illustrate potential design variants. Subsequently, the optimization work itself will be presented. A comparison to experiments is given at the end.

1. THE *SEABRIDGE* PENTAMARAN

1.1. Mission
SeaBridge will utilize the Pentamaran Ro-Pax ferries to move as many as 150 trucks and/or unaccompanied trailers, 220 cars and other vehicles, and 1,800 passengers at speeds up to 42 knots on six routes between eight strategically located ports along the Atlantic and Gulf Coasts. The ferries are designed for open sea transits of at least 10 and as many as 30 hours.

In addition to secure vehicle storage, passenger accommodations will include private berths designed for one to eight persons and individual seating in business class type airline style seats. A full suite of business services and facilities; a wide range of food and beverage services, restaurants, bars; shopping and entertainment options, including casinos and clubs featuring live music, and an extensive range of in-room digital entertainment and full internet access, are provided onboard.

1.2. Design
The initial design was undertaken by BMT Nigel Gee and Associates Ltd. Early studies clearly identified the Pentamaran as the most efficient hullform for the *SeaBridge* application. The advantage of a stabilised monohull over a conventional monohull is the ability to optimise the hydrodynamic qualities of the central hull without the usual restrictions of stability. Normally this allows the naval architect great freedom in the design of the central hull. In the case of the *SeaBridge* a length restriction of 300 m was placed on the vessel. Principal Particulars for the *SeaBridge* are summarized in Table 1.

Table 1: *Principal Particulars*

LOA	300.00 m
LWL	290.00 m
Beam Moulded	45.00 m
Beam Central Hull WL	20.70 m
Design Displacement	30000.0 t
Scantling Displacement	34000.0 t
Main Engines	8 x MAN 48/60B 18V
Waterjets	8 x LIPS/Kamewa
Speed at 90% MCR	41.5 knots

The concept of the Pentamaran is to stabilise a hydrodynamically optimised central hull with four sponsons. The sponsons are to provide the necessary level of stability so as to fulfil regulatory requirements and achieve good seakeeping. The arrangement of the sponsons is shown in Figure 2. For further material on the Pentamaran see (Dudson and Gee, 2001) and (Dudson et al., 2001). See also www.ngal.co.uk.
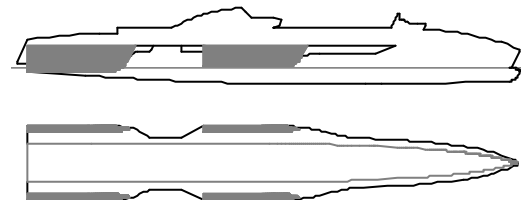

Figure 2: *Pentamaran configuration with central hull and four sponsons*

1.3. Configuration
The vessel is configured with two lower vehicle decks in the central hull and a full breadth vehicle deck above the free board deck.

Access to the vehicle deck is via bow and stern ramps. Passenger accommodation is on the three decks above the vehicle decks. The general arrangement is shown in Figure 3.
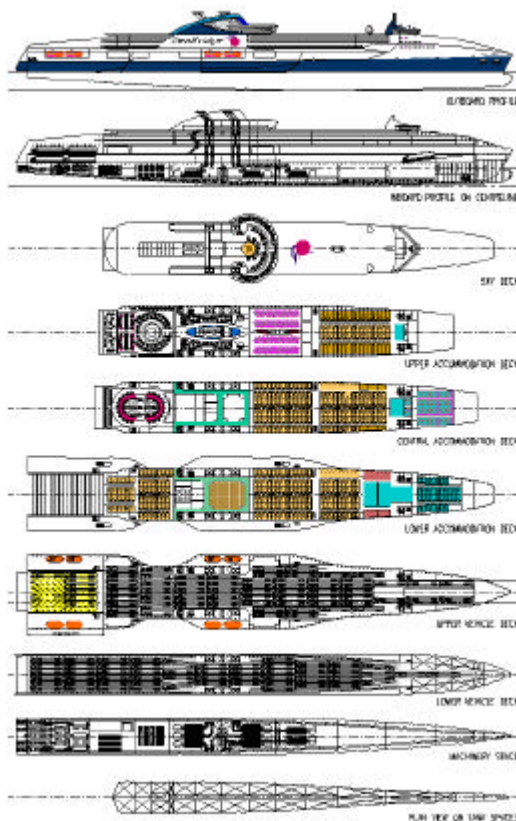
Figure 3: *General Arrangement of the* SeaBridge *Pentamaran*

1.4. Machinery Arrangement

The vessel is propelled by a diesel electric propulsion system which provides for most economic and flexible power plant installation for this application. Medium speed diesel engines burning heavy fuel oil are situated around amidships.

Five waterjets are driven by tandem electric motors positioned close to the transom. The waterjets and electric motors are configured such that with a single jet out of operation, the four remaining waterjets can absorb 100% of the generated power, resulting in minimal speed loss. A sketch of the machinery arrangement is shown in Figure 4.

Figure 4: *Machinery Arrangement*

Installing waterjets on a vessel requires a submerged transom. A submerged transom on a vessel travelling at relatively low Froude numbers, as with the *Seabridge,* can have a significant impact on the total resistance of the vessel. BMT Nigel Gee and Associates Ltd have, therefore, spent a significant amount of time developing the optimum transom design for a waterjet propelled vessel operating at low Froude numbers. The design is developed around the waterjets and the requirements to avoid waterjet ventilation in waves. A sketch of the transom design is shown in Figure 5.

Figure 5: Gulley *transom design*

2. PARAMETRIC MODELLING OF THE CENTRAL HULL

2.1. Parametric Approach

In order to generate and vary functional surfaces of complex shape such as ship hull forms with a degree of freedom suitable for optimization, a parametric approach ought to be followed. The essence of a parametric definition is that a context-dependent and solution-oriented description is established, which allows production of those shapes that are beneficial to performance while still acceptable with regard to the many constraints.

The *FRIENDSHIP-Modeler* grants a high-level definition of hull shapes via form parameters such as beam, deadrise, draft, entrance angles, sectional areas etc. and was therefore selected for the optimization of the Pentamaran's central hull. For details see (Harries and Abt, 1999), (Harries et al, 2001) and (Harries and Heimann, 2003), further information and downloads are available at www.FRIENDSHIP-Systems.com.

2.2. Form Parameters

The shape of the Pentamaran's central hull called for a specific parameterization which was developed by FRIENDSHIP-Systems on the basis of the baseline design by BMT Nigel Gee and Associates Ltd, see Figure 6. The form features were closely examined,

for instance via curvature plots, and suitable form parameters were identified.
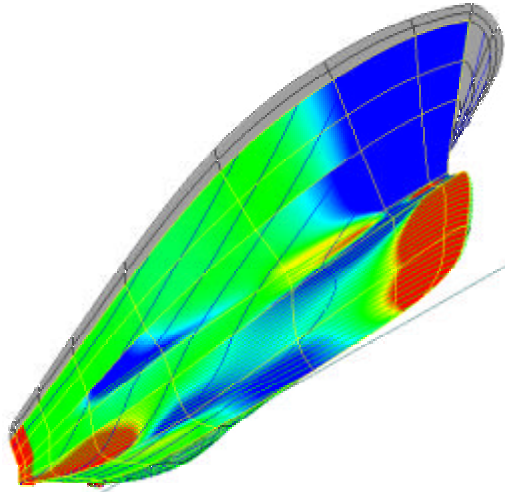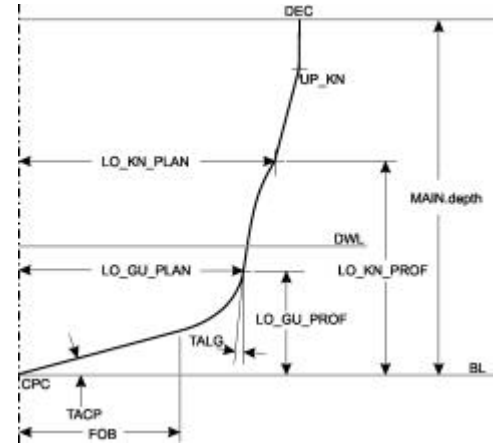

Figure 6: *Curvature plot of the baseline design*

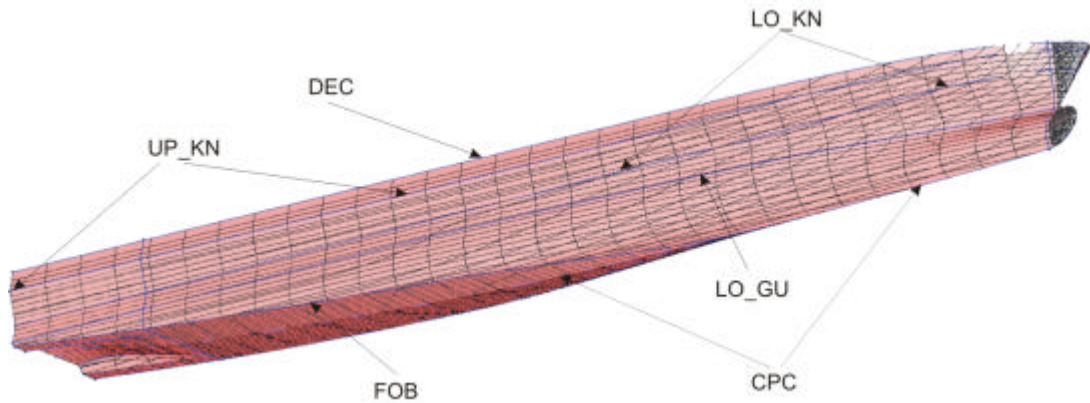Figure 8: *Form parameters for definition of section*

Figure 7: *Hull form and basic descriptors of the* SeaBridge

Figure 7 depicts the central hull generated via the *FRIENDSHIP-Modeler*. The figure shows important shape descriptors, namely the basic curves which are determined from small sets of parameters and which, in turn, provide input for surface generation. Selected form parameters which define a typical section are illustrated in Figure 8. Note that data from the space curves presented in Figure 7 appear here in their plan and profile components, respectively.

Special features of the stern region are presented in Figure 9 – compare to Figure 5 – while the topology of the surface patchwork is shown in Figure 10.
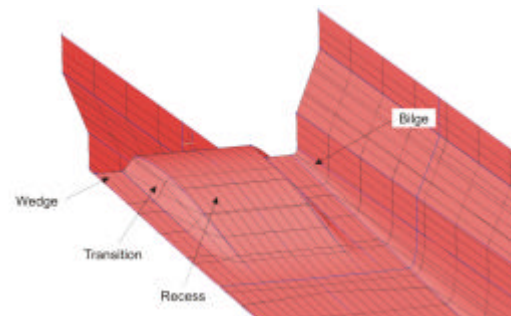

Figure 9: *Special features of stern region (marker shows area of influence if parameter assume non-zero values)*
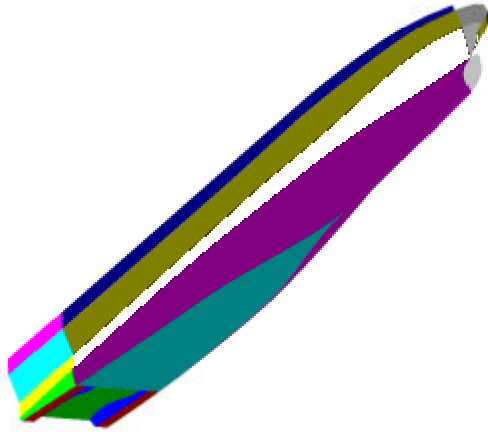
Figure 10: *Surface patches of parametric model*

An important task during an optimization is the control and monitoring of design constraints, see (Abt et al, 2004). The design displacement for instance was fixed at 30000 t. This constitutes an equality constraint which could be handled directly within the *FRIENDSHIP-Modeler* by utilizing the area information from the sectional area curve as input for shape generation. Since the aft body of the Pentamaran's central hull featured little freedom for displacement changes a special mechanism needed to be developed: Firstly, the aft body was generated with respect to the dominating positional constraints of the propulsion unit. Secondly, the actual sectional area curve was computed for the aft body and then continued forward in compliance with the displacement constraint. Finally, the sectional area curve was utilized for the forward body as parametric input. In this way, infeasible designs with regard to displacement could be readily avoided

2.3. Form Variations

Figure 11 illustrates a representative shape variation out of the many which were studied. Here the deadrise was systematically changed from zero to 14 degrees.

Figure 12 gives an impression about the scope of form variations for the aft region. The parameterization allowed a smooth transition from the *Gulley* transom to a more conventional configuration. The *Gulley* however was eventually favoured for the final design (compare to section 1.4).
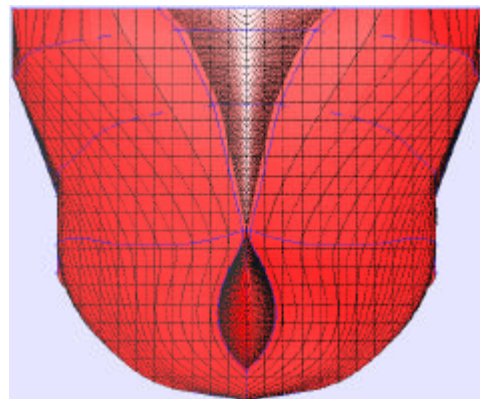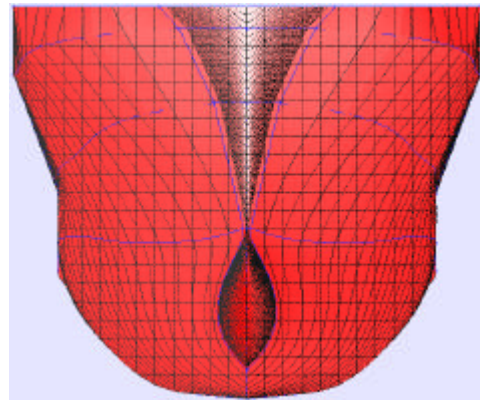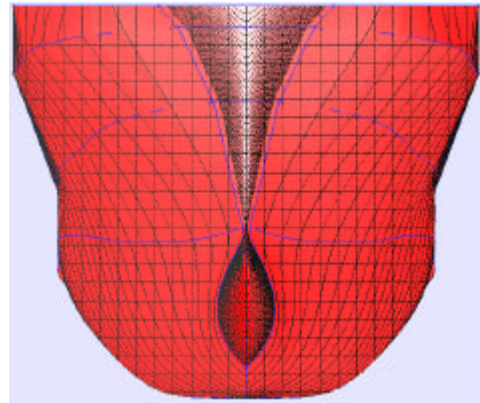

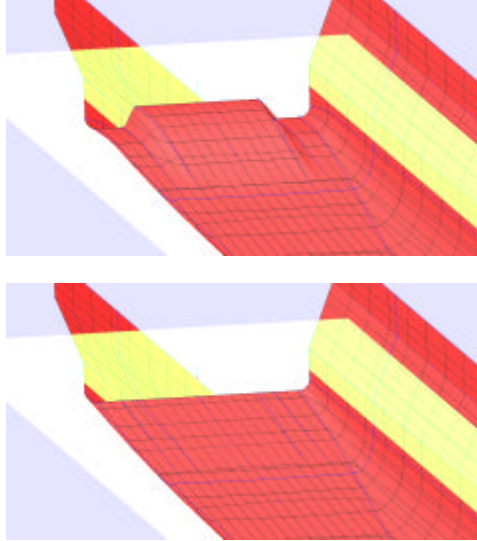**Figure 11**: *Parametric variation via changes in deadrise*

Figure 12: *Parametric variations of stern region*

3. OPTIMIZATION

3.1. Hydrodynamic Analysis

The calm water hydrodynamics was of prime concern in this study, therefore the total resistance was chosen to be the objective of the optimization. The non-linear wave resistance was assessed by means of the potential module of the well-known *SHIPFLOW* code. The wave making resistance was determined by pressure integration and wave cut analyses. Viscous effects were accounted for via the ITTC friction line and a suitably selected form factor.

A systematic panelization study was performed in order to select a good compromise between accuracy, computational demands and robustness. Since model

test results had been available for a similar hull reasonable confidence could be established with regard to the flow code's ability to handle the difficult flow phenomena aft of the *Gulley* transom. The CFD based prediction resulted in resistance estimates below model test results, however, the resistance characteristics were well-captured by CFD for the speed range in question.

3.2. Optimization Approach

Often an optimization programme is beneficially subdivided into two phases of design exploration. In the former, a large set of designs are distributed in the search domain while in the latter promising candidates of the first phase are further improved in a targeted variation.

Figure 13 shows the outcome of a Design-of-Experiment (DoE) which represents the first exploration phase. A fleet of 1000 hull forms were generated, 527 of which passed all constraints and were successfully evaluated by the flow code. A set of 21 form parameters were chosen as free variables for the DoE. In Figure 13 all valid designs are ranked with respect to wave pattern resistance calculated from a transverse wave cut analysis. The dashed line indicates the performance of the baseline. From Figure 13 it can be clearly seen that a substantial number of designs have lower resistance than the baseline. Naturally, many designs also are ranked inferior.

Based on the DoE further optimization runs were undertaken using the Tangent Search Method by Hilleary. This deterministic strategy follows a Hooke-and-Jeeves direct search in connection with a feasible direction approach as soon as inequality constraints
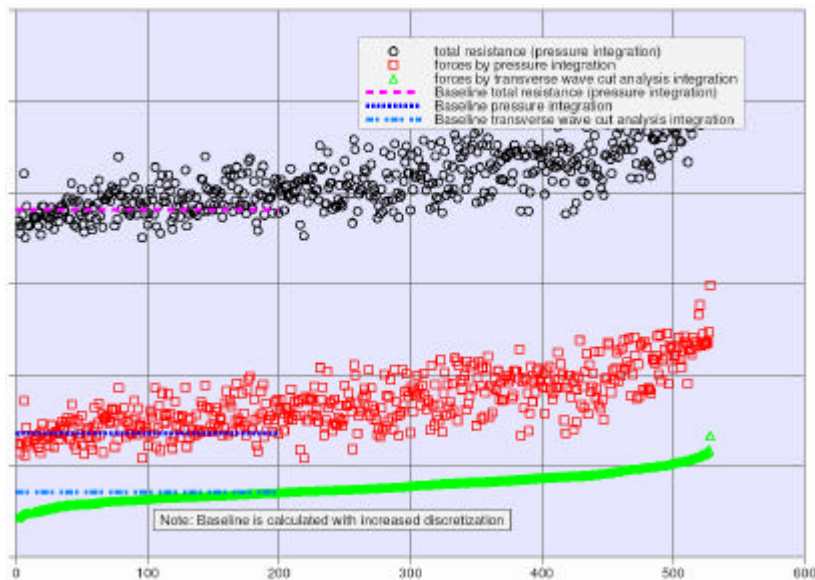

Figure 13: *Resistance estimates sorted by wave pattern resistance*
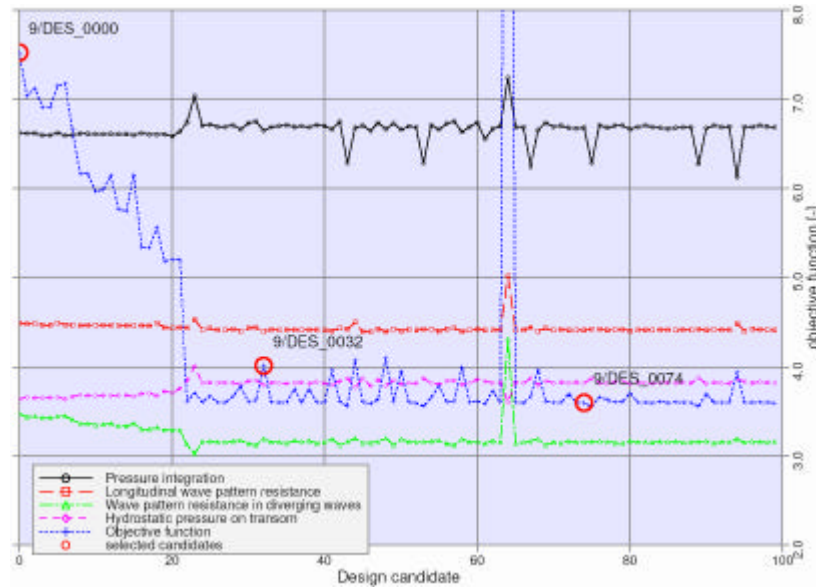*(abscissa: accumulated number of designs, ordinate: various resistance estimates)*

Figure 14: *History of final optimization run*
(abscissa: sequence of design variants, ordinate: combined and normalized objective function)
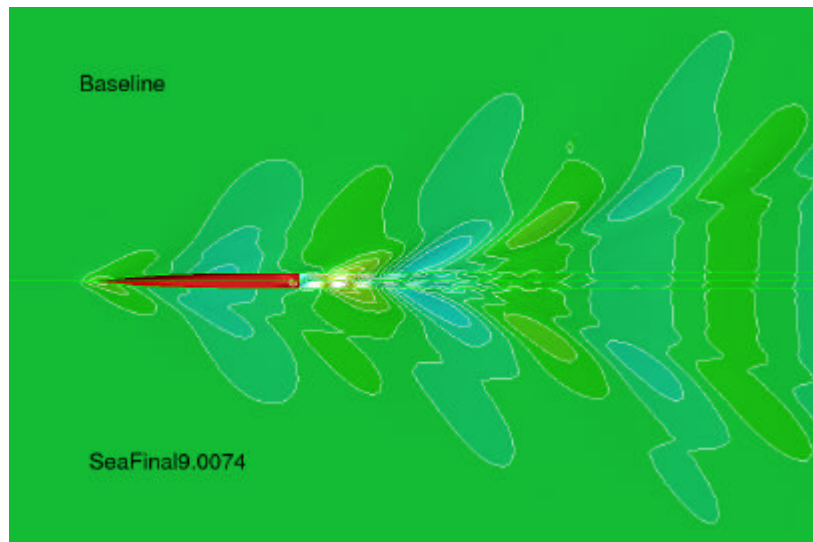

Figure 15: *Wave pattern of baseline and optimized hull* SeaFinal9.0074

are violated.

Figure 14 features the optimization history of the final run from which the best design was identified (SeaFinal9.0074).

3.2. Selected Results

Figure 15 compares the wave patterns of the baseline and the optimized central hull, respectively. (The figure corresponds to the before-and-after pictures of a plastic surgery candidate.) The wave resistance from pressure integration is reduced by about 13.8 %

which yields an improvement of about 5.6 % in total resistance.

4. EXPERIMENTAL VALIDATION

4.1. Test Program

Estimates from the CFD analysis suggested a vessel resistance lower than originally predicted (see also section 3.1). The optimized hull also indicated a further reduction in wave resistance. In order to confirm the resistance predictions from CFD a set of calm water model tests was conducted at

MARINTEK in Norway. Figure 16 shows a photograph from the tests.

Figure 16: Resistance *tests at 40 knots*

4.2. Results

Figure 17 presents wave cuts from both CFD and experiment, 0 and 1 being the position of the forward and the aft perpendicular, respectively. Good agreement in the phase can be seen while the amplitudes from the CFD are smaller than those from the experiments. One possible explanation for the discrepancies is that the wave cut was measured quite far from the hull which may have caused numerical damping in the numerical simulation.

The model test results confirmed the improvement in resistance over the baseline. Figure 18 compares the full scale resistance for the optimized hull as measured from model tests against the predicted resistance for the baseline hull at 30000 t.
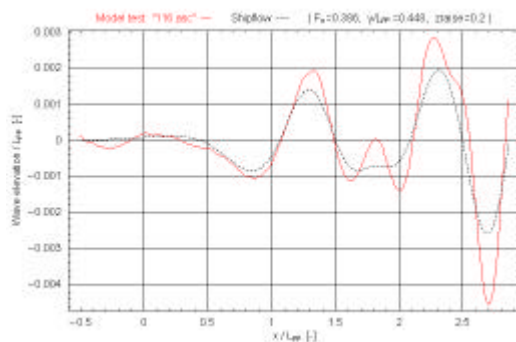

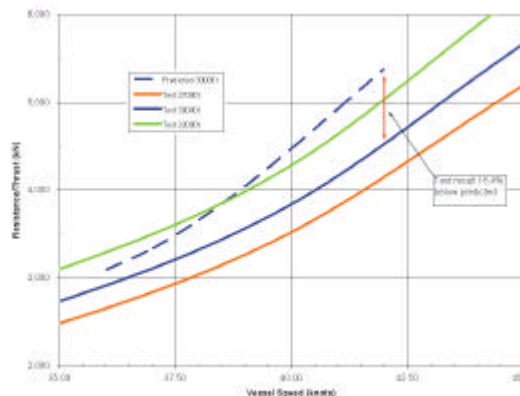**Figure 17**: *Wave cut from CFD and model tests*

Figure 18: *Model test results for three displacements*

5. CONCLUSIONS

The process of parametric optimisation through CFD provides the designer with a tool which significantly enhances the usability of CFD and results in a truly optimized hull, rather than an improved hull. Naturally, the user's knowledge and understanding of CFD is vital as well as an appreciation of the limits of the flow code. A suitable parameterization of the problem is essential to reduce the number of free variables and, consequently, the overall number of designs for which a CFD simulation is to be undertaken. The application of formal strategies to fine-tune the Pentamaran's central hull for high-speed sea transportation services proved to be successful.

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AUTHORS' BIOGRAPHY

Ed Dudson graduated from the University of Southampton in 1990 and joined Nigel Gee and Associates the same year where he has worked continuously with the exception of a year's sabbatical in MARINTEK. He is Director of Ship Design for BMT Nigel Gee and Associates Ltd. In October 2004 he was elected to the board of Directors of BMT Nigel Gee and Associates Ltd. Ed Dudson is a Chartered Engineer and Member of the Royal Institute of Naval Architects.

Stefan Harries is managing director of FRIENDSHIP-Systems, a design consultancy that he co-founded in 2001. He studied mechanical engineering at the Technical University of Darmstadt and naval architecture at both the University of Michigan (MSE in 1990) and the Technical University Berlin (Diplom-Ingenieur in 1992). In 1998 he received his doctoral degree from TU Berlin, following five years as scientist with Prof. Nowacki. He was head of Marine Hydrodynamics at the Berlin Model Basin VWS (1998 to 2000) before he became head of TU Berlin's research unit Design and Operation of Marine Systems (2001 to 2003). Since 2004 he is full-time with FRIENDSHIP-Systems but keeps to be associated with TU Berlin as lecturer for Computer Aided Engineering.