THE FANTASTIC RORO: CFD OPTIMISATION OF THE FOREBODY AND ITS EXPERIMENTAL VERIFICATION

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ABSTRACT

The paper discusses the hydrodynamic optimisation of the bulb and forebody of a RoRo vessel. The study was conducted in parallel by a number of hydrodynamicists using different approaches and software tools for shape optimisation. Each synthesis model consists of a CAD system for design and modification of hull forms, a CFD code for evaluation of calm water performance and an optimisation tool. Shape modifications were carried out based on a parametric approach, that is, the hull geometry was modified by varying a number of significant form parameters to achieve the desired improvement in calm water performance.

Different optimised shapes were identified and cross computed using three different CFD codes. One of the best performing hull shapes was then model tested for a comparison with the original geometry.

The results of CFD computations and model tests support the adopted general approach to hydrodynamic optimisation and provide a good overview of the role and perspectives of the use of CFD and optimisation techniques in ship design.

The work presented in this paper has been carried out within the EC funded project ‘Functional Design and Optimisation of Ship Hull Forms’, G3RD-CT-2000-00096.

1. INTRODUCTION

Hydrodynamic optimisation of hull forms is an important aspect of ship design and involves issues that can sometimes haunt designers' dreams.

CFD plays an important role in this optimisation process, which takes place in the early phase of ship design and actually consists of an iterative procedure of modifying hull forms, evaluating them using CFD calculations, and, based on the computed results, further modifying the hull until it performs satisfactorily.

In recent years an effort has been made, and is still being made, to improve the efficiency of the hydrodynamic optimisation process, by developing a rational way to carry out hull form modifications and CFD computations, and to efficiently drive shape changes to converge to beneficial solutions.

The use of formal optimisation techniques and the development of CAD tools for parametric modification of hull forms play an important part in this type of rationalised approach.

Within this framework, this paper presents a comprehensive study carried out in the course of the EC funded Project FANTASTIC [1] on the hydrodynamic optimisation of the forebody of an imaginary but very realistic RoRo vessel representative for contemporary designs.

The study consists in a number of different Project Partners taking up the task of optimising the forebody of the same RoRo vessel, using software tools for hydrodynamic optimisation set up during the project. As a result, a number of different optimised forebodies were produced, and, after cross computing the different solutions, one of these has been model tested against the original shape.

The results of the CFD computations and the comparison of calculation and experiment were found to support the approach to design optimisation adopted in the project and provide a useful overview of the role and perspectives of the use of CFD and optimisation techniques in ship design.

2. THE HULL AND THE PROBLEM TO BE SOLVED

The design task discussed is the optimisation of the bulb and forebody of a RoRo vessel, shown in Figure 1. The hull was called FANTARORO hull after the name of the project FANTASTIC. The original hull has a rather pronounced bulbous bow whose top is just below the design waterline.

Bulb optimisation is a rather typical task that designers and consultants have to tackle. In this type of task the designer has usually some freedom in changing the shape of the bulb, while the overall hull volume distribution cannot be changed much and also length variation must usually be limited. This is because at the stage when the shape of the bulb is closely studied the main ship particulars and internal arrangements have been already decided upon.

In the case of the FANTARORO, it was agreed that changes and faring of the shape would be limited to the fore half of the hull.

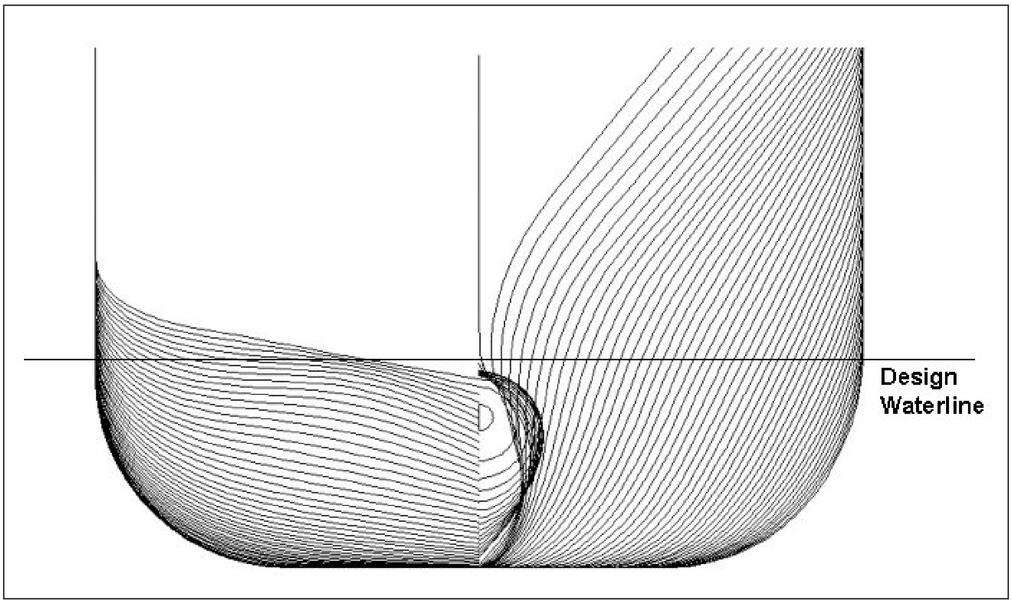

Figure 1
Body plan of the FANTARORO

Table 1 below lists the ship's main particulars.

Table 1 - Main particulars of FANTARORO

Lbp	123.0	m
Max Beam	19.50	m
Draft	5.0	m
Displacement volume	6759.4	m3
Longitudinal Centre of Buoyancy from AP	57.91	m

The optimisation task has been carried out with the objectives and constraints summarised in Table 2 and 3. All the calculations were carried out for a fixed speed equal to 21.0 knots, corresponding with Fn = 0.312.

Table 2 - Objectives

Minimise total resistance RT RT = RW + (1+k) RF RW being the wave resistance, evaluated with CFD calculations RF being the frictional resistance calculated according to the ITTC formula and a fixed form factor

Table 3 - Constraints

Displacement witihin +/- 1.0 % of original value
Longitudinal centre of buoyancy +/- 1.0 % of original value
Distance of bulb tip from AP ≤ 128.0 m, this meaning possible bulb elongation ≤ 1.0 m
Hull modifications allowed only in the fore part of the hull from midship to the bulb tip

The optimisation task has been carried out by the authors with different procedures that shared two common features: the use of CFD tools for performance assessment and, importantly, the same rational approach to hull form optimisation, as discussed in detail in section 3.

3. CFD OPTIMISATION

3.1. General

The optimisation methodology developed during the project FANTASTIC is based on CFD predictions. The optimisation process is actually an iterative process consisting in modification of the hull forms, evaluation of their hydrodynamic performance as predicted by CFD calculations, and, based on this assessment, further shape modifications until the an advantageous solution has been found.

This is not a new approach of course; the interest of the methodology lies in the effort to turn the approach into a fully rational procedure. While usually hull form modifications are done manually by the designer and also decisions about shape changes are largely based upon individual decisions and experience, the approach developed in FANTASTIC and applied to the FANTARORO optimisation aims at being more rational and is based on two key points:

- hull form modifications are dealt with using a parametric approach, in which the designer decides which form parameters he or she wants to modify and the hull shape is changed accordingly
- formal optimisation techniques are used to address and efficiently solve the optimisation problem.

A scheme of the optimisation procedure is shown in Figure 2.

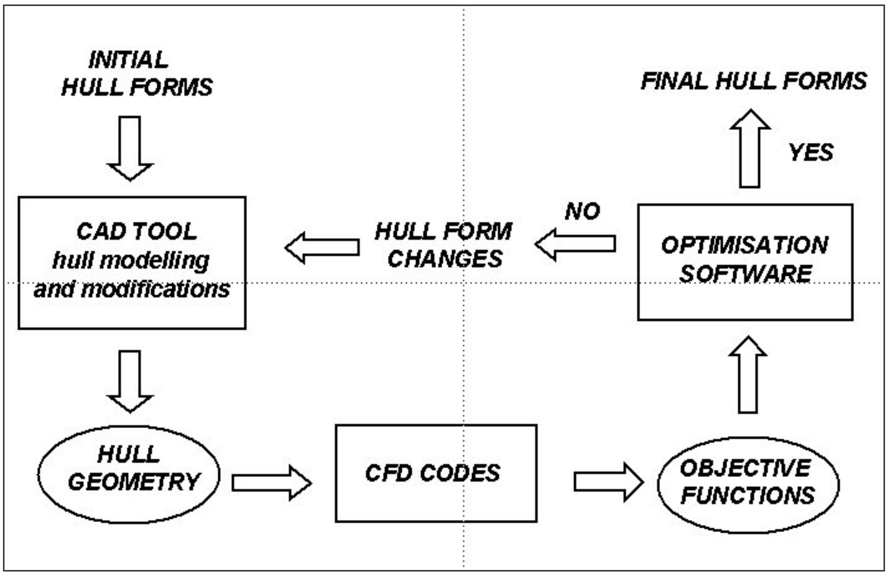

Figure 2 - General scheme of optimisation approach

Based upon this general scheme, in the course of FANTASTIC the authors have set up their own software tools for optimisation using the CAD and CFD tools of their choice. The CFD tools are all potential flow panel methods.

Table 4 summarises the characteristics of the different optimisation tools.

Table 4 - Optimisation approach

Setup by	**CAD for hull modelling and modification**	**CFD**	**Optimisation toll/procedure**
MARIN	GMS (1)	RAPID (2)	Systematic variations
TUBerlin	FRIENDSHIP-Modeler (3)	SHIPFLOW (4)	modeFRONTIER (5)
HSVA	NAPA (6)	Nu-SHALLO (7)	modeFRONTIER
CETENA	FRIENDSHIP-Modeler	WARP (8)	modeFRONTIER
CHALMERS UNIV.	FRIENDSHIP-Modeler	SHIPFLOW	Xopt (9)

Software code developed by and property of:

(1) MARIN,The Netherlands; (2) MARIN,The Netherlands;
(3) TUBerlin / FRIENDSHIP-Systems, Berlin, Germany; (4) FLOWTECH, Gothenburg, Sweden
(5) ESTECO, Trieste, Italy; (6) NAPA Oy, Helsinki, Finland; (7) HSVA, Hamburg, Germany;
(8) CETENA S.p.A., Genova, Italy; (9) Alfgam Optimering AB, Stockholm, Sweden

In order to take advantage of formal optimisation techniques, hull form modifications must be described and dealt with in terms of a number of parameters that are let free to change during the optimisation process. All of the CAD systems in Table 4 can deal with parametric variations, though in different ways. This is actually where the main differences between the different setups lie.

The FRIENDSHIP-Modeler is based on a fully parametric approach to hull form description and modifications. This means that hull forms and their variants are completely described by means of a flexible set of form parameters.

GMS and NAPA make use of what might be called a partially parametric approach. In the case of GMS hull forms are described as NURBS surfaces, and parameters are used to define hull from modifications through shifts of the NURBS surfaces control points [2]. In the case of the NAPA System, the parameters that can be varied to modify the hull forms are mostly point coordinates and local angles which are used to modify the grid of lines defining the hull shape.

3.2 The FANTARORO case: approaches and solutions

For the optimisation of the FANTARORO's bulb and forebody, each of the parties involved has used their own optimisation set-up, as presented in Table 4. Prior to that, SIREHNA carried out a preliminary study of the FANTARORO's forebody using different calculation chains incorporating nu-SHALLO and various CAD systems.

For the optimisation task, each party has been free to decide about the bulb and forebody modifications and the optimisation strategy, that is, the type of optimisation technique to be used. Table 5 lists the different approaches.

Table 5
Different approaches to the FANTARORO optimisation

optimisation by	**Parameters used to modify bulb and forebody's shape**	**Optimisation strategy**
MARIN	Bulb length, height, width, waterline angle and curvature. Forebody changes too in order to achieve a good fairing of the bulb into the main body.	The parameters have not been varied simultaneously, but 2 to 3 at a time in successive steps. At each step, an assessment of the results has been made to decide about further modifications.
TUBerlin	Bulb parameters Bulb length, location of tip and top, area and shape of bulb section at the fore perpendicular; bulb sectional area distribution. Forebody's parameters Entrance angle, area coefficient of fore portion of waterplane, sectional area curve parameters.	Parameters were varied simultaneously. A combination of Design of Experiments, MOGA (Multi Objective Genetic Algorithm) and Nelder Mead SIMPLEX was used. See [3] for further details.
HSVA	HSVA have used the hullform parametrisation provided by NAPA. Amongst the parameters provided in there, the following have been chosen: bulb length, height of bulb at 2/3 of bulb's length and bulb width at this same location, longitudinal location of bulb section with maximum width, vertical location of bulb tip. Shape changes were limited to the bulb with virtually no change to the forebody.	MOGA
CETENA	Bulb parameters Bulb length, location of tip and top, area and shape of bulb section at the fore perpendicular; bulb sectional area distribution. Forebody's parameters Entrance angle, area coefficient of fore portion of waterplane.	Design of Experiments (parametric investigation)
CHALMERS UNIV.	Bulb length, location of tip and top, area and shape of bulb section at the fore perpendicular; bulb sectional area distribution. Only parameters describing bulb shape were used.	Gradient based optimisation algorithm based on method of Moving Asymptotes

From the table it can be seen that most parties adopted an approach in which all the chosen variables are varied simultaneously with variations driven by an optimisation algorithm (MOGA or gradient based). MARIN adopted a different approach in which in a number of successive steps, based on inspection of the last computed wave pattern, parametric deformations were defined that were expected to lead to the desired further changes. These parameters were then varied a few at a time and the best values selected. This step by step process was continued until a satisfactory result was obtained ([2]).
All partners used RT as the figure of merit of the optimisation process; most of them calculated RW by means of both pressure integration and wave pattern analysis, as the two methods can provide different results and it is advisable to check both. In addition, wave cuts and pressure distribution were inspected. The different optimisation processes led to the rather different shapes shown in Figure 3. All of the optimised shapes lie within the agreed constraints.

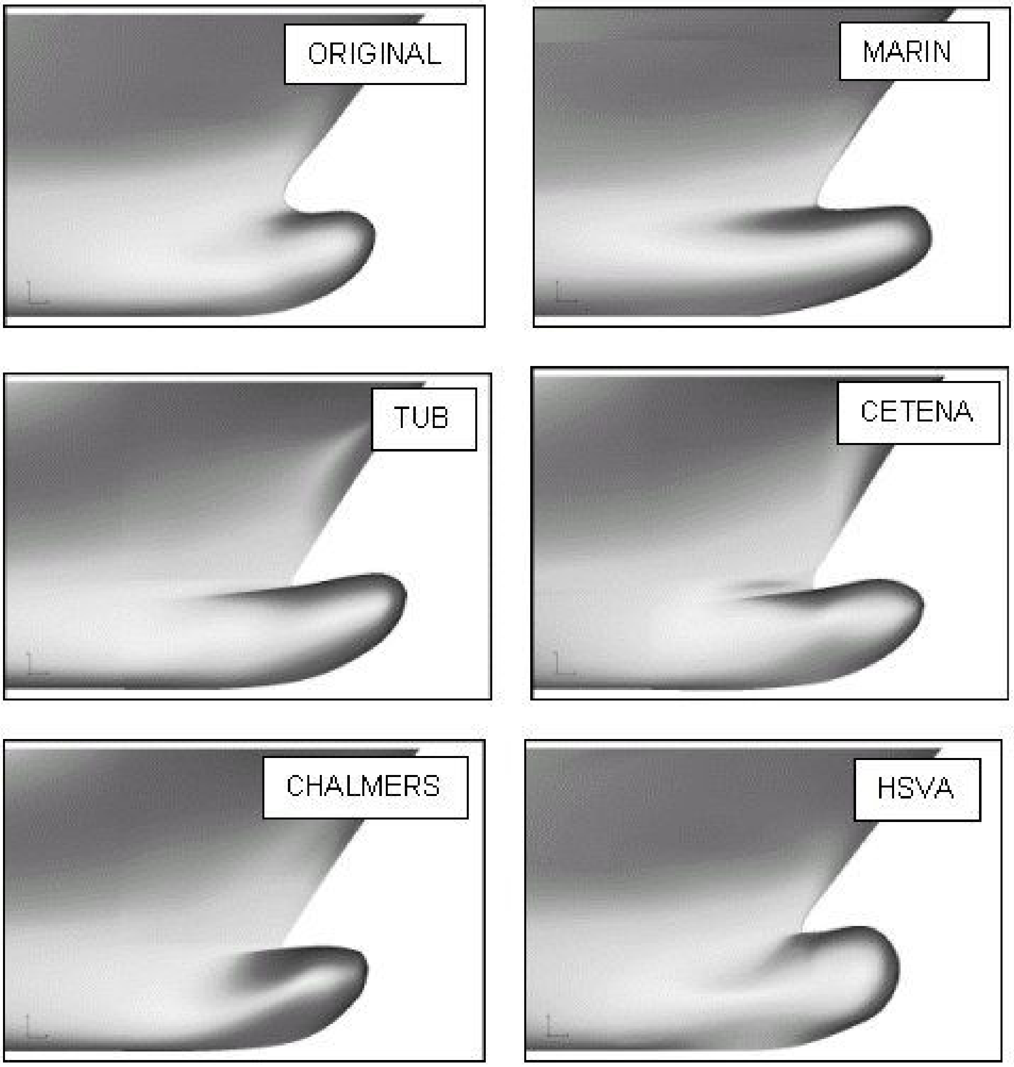

Figure 3 – Side view of original and optimised shapes

One of the reason for the differences is related the different parameterisations adopted for the modifications of the bulb and forebody. This si probably the most important aspect. Also the use of different optimisation techniques plays a role, and definitely the different background and past experience of the people involved.

In the optimisations, the hydrodynamic performance of the different shapes had been assessed with different CFD tools (Table 4). Therefore, to see how they actually compared and to choose one shape to be model tested, cross computations were made, i.e. all optimised shapes were evaluated using three different panel codes. This is discussed in the next section.

4. CROSS COMPUTATIONS

Cross Computations of the different 'optimal' shapes have been carried out with RAPID, SHIPFLOW and nu-SHALLO. The number of panels used on the hull was 1615 for SHIPFLOW, 2232 for nu-SHALLO and 3000 for RAPID. Also free surface densities were different, RAPID's being the densest.

Cross computations have allowed a ranking of the different solutions, besides a number of interesting considerations on the level of consistency between the panel codes, the accuracy of resistance evaluations, and requirements for a successful use in optimisation; which unfortunately cannot be discussed in detail here. What can be said here is that the results of the three set of computations show differences, partly because of the different panel densities used. However, they provide a number of common indications that allow a proper ranking of the design solutions.

Figure 4 shows a comparison of the wave cuts at a distance equal to 0.25 Lbp from the hull's centreplane, as calculated with RAPID.

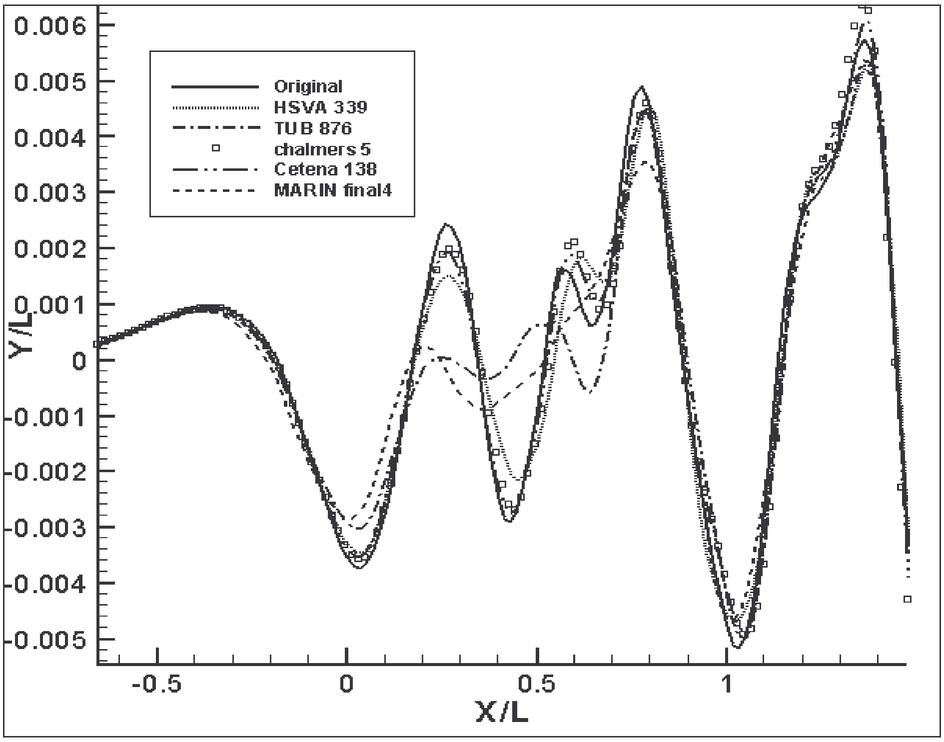

Figure 4 – Comparison of wave cuts

It can be seen that there is a group of solutions with very similar performance, and two designs that show a particularly good behaviour, MARIN's and TUBerlin's. These hull forms generate a bow wave cancellation which is favourable from a wave resistance point of view and is not present in the other designs.

A similar trend could be observed from the wave cuts calculated with nu-SHALLO and SHIPFLOW.

Table 6 presents the ranking of the different solutions as obtained in the cross computations. The ranking is primarily based on wave pattern resistance, as this is considered more reliable than wave resistance obtained by pressure integration.

From Table 6 the trend of Figure 4 is confirmed. TUBerlin's and MARIN's solutions perform very well with a marked reduction in resistance.

Comparing TUBerlin's and MARIN's design solution, one can see that TUBerlin's is less traditional with a pronounced fore shoulder; MARIN's is more conventional except for a pretty large bulbous bow. The two designs were obtained with rather different procedures, MARIN's with a step by step analysis of the effect of shape modifications on the hull's performance, TUBerlin's with an automatic optimisation process driven by genetic algorithms.

Table 6 – Summary of cross computations.
Comparison of wave resistance values of initial and all optimised designs, as computed by the 3 panel codes

	Original design	**MARIN's design**	**TUBerlin's design**	**HSVA's design**	**CETENA's design**	**CHALMERS' design**
Nu-SHALLO %	100.	75.6	75.0	81.8	81.5	77.3
SHIPFLOW %	100.	93.7	92.4	99.4	98.9	97.5
RAPID %	100.	87.5	87.5	95.2	99.7	102.4

The model tests having been planned for only the original and one modified shape, a choice had to be made between MARIN's hull and TUBerlin's. computations. It was decided to test TUBerlin's hull for the interest of testing a less conventional shape produced by an automatic optimisation process.

Prior to model testing, TUBerlin actually produced an additional design.

This design's features are similar to the previous hull's except for a less pronounced fore shoulder. The design proved to perform even better than its predecessor as determined by CFD calculations with both RAPID and SHIPFLOW. Figure 5 shows a comparison between the new TUBerlin design and the original one, in terms of wave pattern, while Table 7 shows the predicted reduction of both total resistance and wave pattern resistance as calculated with RAPID and SHIPFLOW.

Table 7 – Predicted improvement of TUBerlin's design in RT and RW in comparison to original hull

	RT reduction	**RW reduction (wave pattern analysis)**
RAPID prediction	4.8 %	13.5 %
SHIPFLOW prediction	6.1 %	16.0 %

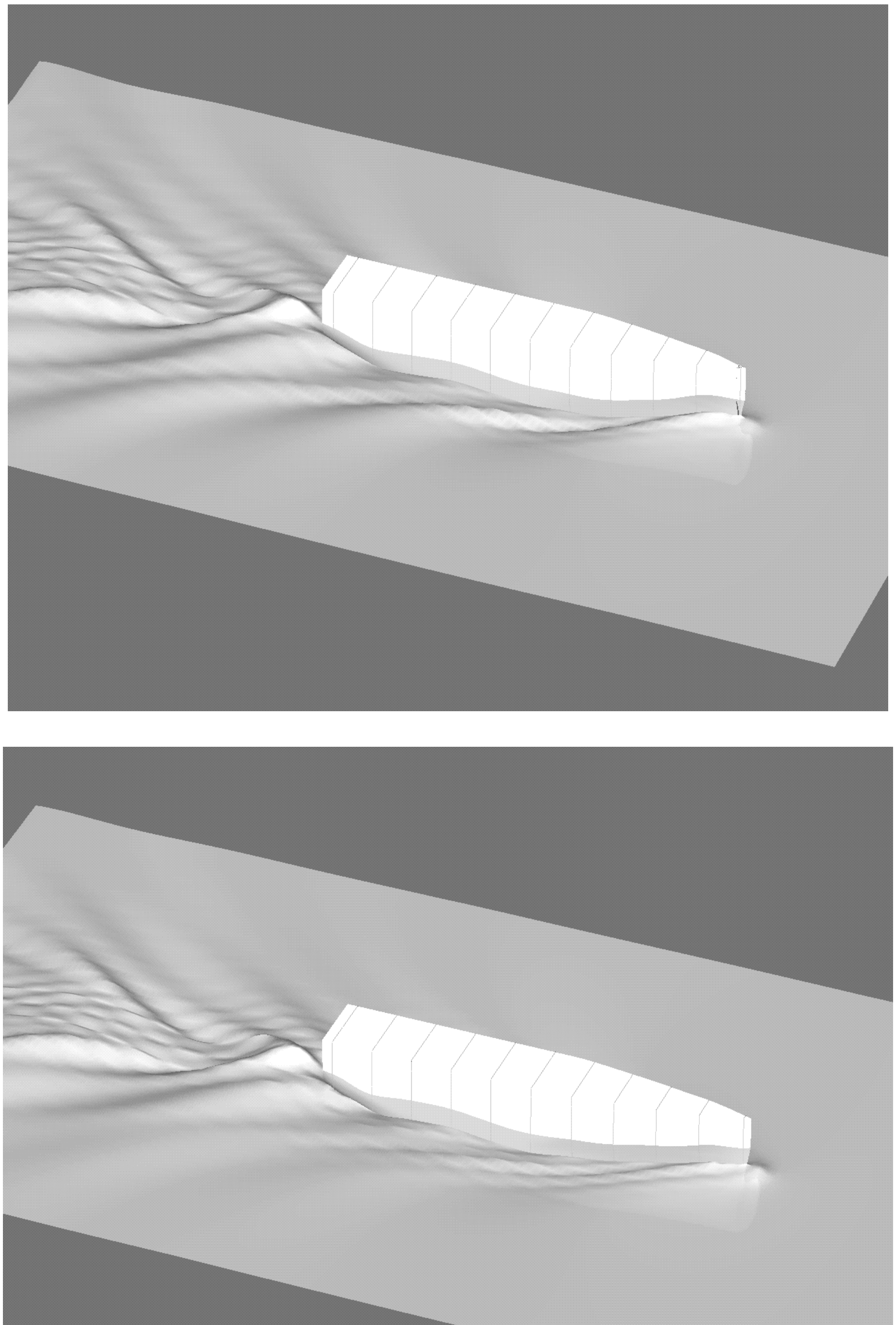

Figure 5
Wave pattern generated by original hull (top) and modified TUBerlin design (bottom), as predicted by RAPID. Vertical scale 3 times magnified.

5. EXPERIMENTAL VERIFICATION

The usefulness of the optimisation hinges upon the validity of the resistance and wave pattern predictions, at least in a comparative sense. To check the amount of improvement achieved in this purely computational process, both the original hull form and the optimised version with a new forebody have been model tested in SSPA's towing tank, to a 1:25 scale. Resistance and wave cut measurements have been carried out.

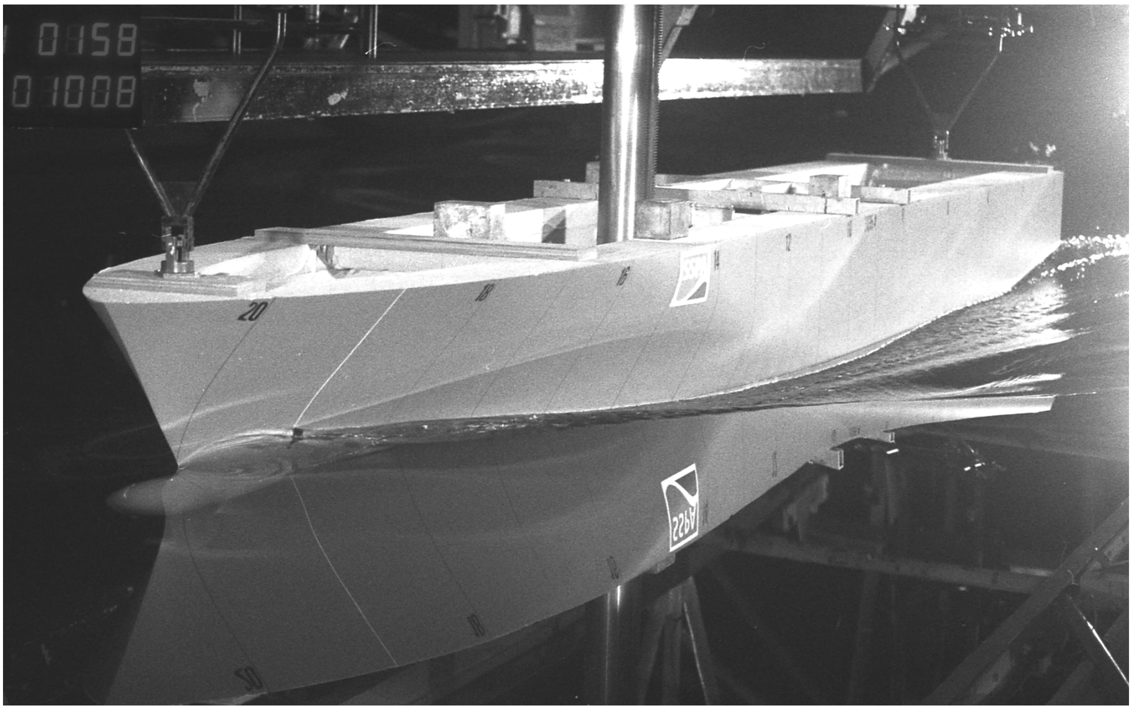

Figure 6 - Model trials at SSPA

From the measurements, a reduction of the total resistance at full scale was deduced of 2.3 % at 21 knots; an improvement but considerably less than the predictions in Table 7. In analysing this difference, the difficulty arises of estimating the viscous resistance component. The optimisation was driven by the wave resistance predictions, while viscous resistance was simply estimated using a fixed form factor 1 + k = 1.085. Variations in the form factor were left out of account, but will take place in reality and may obscure the improvement achieved in the experiments.

Therefore, low-speed tests have been done and individual form factors have been determined for the original and optimised hull form, being 1+k = 1.06 and 1.072, respectively. This suggests that the viscous resistance has increased by about 1.4 %, due to a slightly larger wetted area and due to the stronger curvature at the bilges.

Using these form factors we arrive at an experimental reduction of the residual resistance of 7.4 % at 21 knots. This is less than the predicted wave resistance reductions of 13.5 to 16 %, but still means a significant improvement. Evidently, not too much value should be attached to the precise magnitude of the experimental reduction of the residual resistance: the difference in measured model resistance amounted to just 2 %, and there is a significant uncertainty in the form factors because of some scatter in the low speed prohaska plot, which makes it difficult to make an accurate extrapolation to get the form factor. This has a large effect on the residual resistance since the latter is just a quarter of the total resistance at model scale.

A more precise insight in the validity of the predictions is obtained from a comparison of the wave pattern as captured via wave cuts. Fig. 6 shows measured longitudinal wave cuts at 0.48 Lpp off the centreplane, for the original and optimised hull form; and compares these with the corresponding cuts predicted several months earlier. It appears that the agreement is quite good, both for the wave elevations and phases themselves and for the differences between the two models.

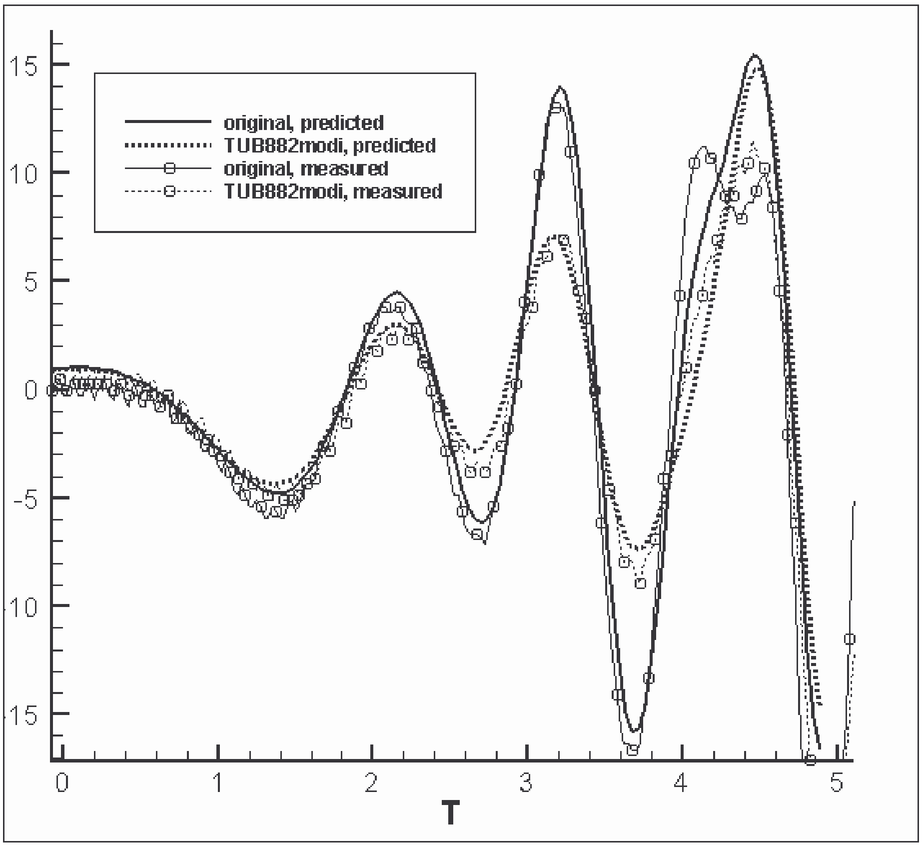

Figure 6 – Comparison of calculated (RAPID) and experimental wave cuts

Table 8 compares predicted and measured values of the residual resistance, sinkage and trim (from RAPID) for original and optimised hull. Overall, the predictions are accurate.

Table 8

	original		**optimised**	
	exp.	predicted	exp.	predicted
wave resistance coeff.	0.00116	0.00120	0.00107	0.00107
sinkage [m]	0.325	0.321	0.324	0.322
trim [deg]	0.10	0.08	0.12	0.10

In summary, the experiments have confirmed the improvements in wave resistance and wave making predicted; although the reduction of the wave resistance seems to be less than predicted, and is partly offset by a slight increase of the viscous resistance. In general the results give confidence in the use of these computations in an optimisation context, even for a starting point which already is a good and realistic design.

6. CONCLUSIONS

A comprehensive optimisation study of the bulb and forebody of a RoRo vessel, the so called FANTARORO, has been discussed in this paper. The study consisted in a shape optimisation task carried out in paraller by a number of hydrodynamicists using different CFD tools, followed by an experimental validation of the CFD results for one of the most promising optimised shapes.

In all cases, the CFD optimisation has been carried out using a synthesis model consisting of a combination of a CAD system for the definition and modification of the hull's shape, a CFD code for potential flow calculations and an optimisation tool. Various CAD systems and CFD codes were used by the involved parties who also adopted different approaches to optimisation.

The CFD study identified a number of different optimised shapes. One of the most promising shapes has been model tested together with the original shape to validate the computed optimisation results.

The model test have confirmed the improvement in the hydrodynamic behaviour of the optimised shape with respect to the original one. The actual reduction in the total resistance as measured in the model basin is different from the predicted reduction, partly because of the simplified model adopted for the evaluation of viscous effects in the optimisation procedure.

On the whole, considering that the original shape is rather well performing already, the model test results seem to prove the effectiveness of the general approach to design optimisation adopted for the study.

Because of the number of parallel CFD studies of the same design and of the experimental validation of the calculation results, the FANTARORO study has been a unique exercise and has allowed an interesting discussion on the use of CFD tools and optimisation techniques for hull design.

The study has stressed that the success of a shape optimisation task depends on a number of important issues.

A first important requirement is the capability to generate smooth hull shape variants by varying a number of suitably selected form parameters. This is actually the key point to be cared for to make design optimisation a fast and reliable process.

Another important aspect is the selection of the right optimisation criteria, which must take into account the goal of the optimisation task, but also the features, capabilities and limitations of the CFD tools used to simulate the hull's hydrodynamics.

Finally, it was found that, when panel codes are used to evaluate calm water behaviour, a dense panelling is necessary for a correct prediction of the effects of shape modifications on hydrodynamic performance.

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8. ACKNOWLEDGEMENTS

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