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Optimal Shape Design of a Surface Combatant with Reduced Wave Pattern

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Optimal design techniques have received considerable attention in many industrial contests: on contrast, the application of automatic optimization to the hydrodynamic ship design has not yet reached the same maturity. Nevertheless, numerical tools, combining together modern computational fluid dynamics and optimization methods, can aid the ship designer, enhancing the operational performances and reducing development and construction costs. Moreover, specific problems that arise during the design phase could be corrected with the aid of a properly defined optimization problem solution.

In this paper, a new approach to the design methodology, involving together designer experience and optimization strategies, is presented. The forebody geometry of a frigate ship, whose original design produced steep bow wave and consequently hydrodynamic noise near the sonar dome due to breaking, has been modified to reduce wave height and suppress the breaking. The numerical optimised geometry has been produced and tested against the original design to experimentally assess the validity of the procedure.

Ship Design methodology

In common practice, the design of a ship involves several cycles, in which desk studies and model basin experiments are coordinated: solutions coming from the design department are tested in the model basin, and then the experimental results drive the new solution to be produced, as soon as the designer's requirements are fulfilled. A fully automatic and non-interactive alternative approach may be based on a use of optimal design methodology. This choice may lead to a sensible cost reduction in the design phase, since effort in the experimental testing is drastically decreased. A trade-off between these two proposals may be the best choice: an initial solution, to be tested, is proposed by the design team, and then further improved by the CFD group. A final test will verify the so obtained results.

In this paper this strategy is depicted. An alternative solution for the bulbous bow of an already operating frigate ship was tested in the basin. This proposal becomes the parent hull form for an *ad hoc* optimization problem performed by the CFD group. The solution of the optimization problem has been experimentally tested, and the results compared against the performances of the alternative solution.

Problem description

A naval combatant, with a bulbous bow including the sonar dome, is usually applied in anti-submarine (ASW) activity. During these types of missions, a hydrodynamic noise problem was encountered. Due to the presence of the large sonar dome, a high and steep bow wave was observed at the speed on 10-12 knots. As a consequence, depending also on the sea condition, wave breaking may be cyclically produced and, because of the hydrodynamic noise, the effectiveness of the sonar may be greatly reduced.

In figure 1, a picture taken during the towing tank tests (in calm water) of the original unit, is reported. The wave pattern produced by a 6.5 m model at the critical speed (12 knots in full scale) shows a deep



Fig. 1 A view of the experimental tests on the original bow.

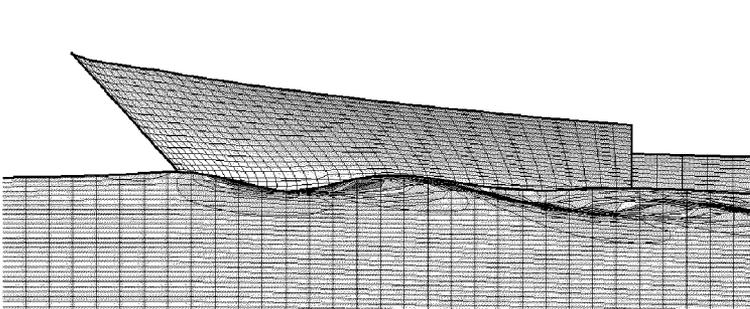


Fig. 2 Numerical verification on the PHF in the same conditions of fig. 1.

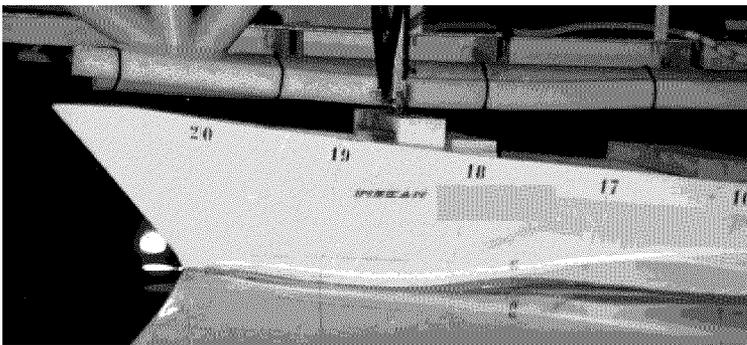


Fig. 3 A view of the experimental tests on the modified bow in the same conditions and viewpoint of fig. 1.

hollow in the nearby of station 19. For the wave lengths produced at model scale, the action of the surface tension tends to reduce and postpone the incipience of the breaking, preventing air bubble entrainment in water and hence reducing both noise and post breaking phenomena with respect to the behaviour at full scale. Nevertheless, it is evident that the crest between stations 19 and 18 shows the insurgence of breaking phenomena.

In order to resolve this problem, the design team has produced an alternative bulbous bow, moving down the sonar dome location. As a consequence, the interference between the dome and the free surface has been decreased, and the wave elevation has been lowered. In general, the benefits of this choice are questionable, since the bulb is pushed outside the projection of the ship hull on the front plane, hence increasing the frontal area of the ship and augmenting the ship's drag. Moreover, as the depth of the ship increase, a possible reduction of the operability of the ship in shallow water is also encountered. Anyway, the alternative solution proposed by the shipyard was accepted by the purchaser and tested in the INSEAN model basin.

The tests confirmed the goodness of this choice, since the bow wave at the critical velocity was greatly reduced and the incipient breaking was suppressed, as reported in fig. 3.

However, the suppression of the breaking wave near the bow did not mean that a

truly optimal solution for the problem was found and a better design may be able to produce even a lower wave pattern. For this reason, starting from the alternative solution (from now on referred as Parent Hull Form - PHF), a numerical optimization cycle has been performed, searching for a better design.

The optimization problem

The numerical prediction of the hydrodynamic noise is quite a difficult task, the accuracy required on the pressure value being too high for available computational tools. Beside that, the numerical prediction of the incipient breaking is another complicated problem, mainly due to the difficulties

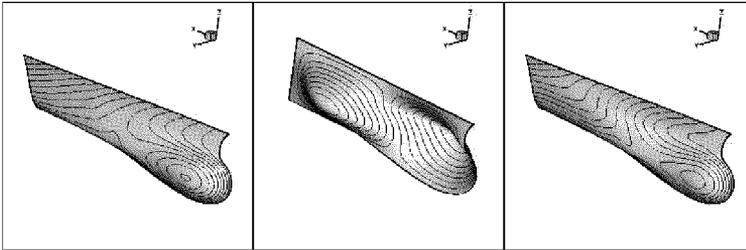


Fig. 4 An example of hull surface modification by superimposition of a Bezier patch. A Bezier surface (middle) is summed to the original hull surface (left), obtaining a modified geometry (right).

encountered in the free surface treatment. To solve the problem, the wave pattern has been estimated by using a steady free surface potential flow model, previously developed and currently applied at INSEAN for the wave resistance computations [2]. This solver is able to compute the wave pattern around a ship with good accuracy. As a consequence, the slope of the wave profile along the hull has been adopted as objective function inside the optimization cycle. The lower the wave slope, the less the probability of breaking waves occurrence near the hull.

As to the geometrical constraints, small variations of the PHF are allowed, the maximum displacement of each grid point being of 1 meter (ship scale). The keel line of the PHF is not modifiable, and the region of the hull to be varied is the same as the one used by the design team in producing the alternative design. The volume of the bulb

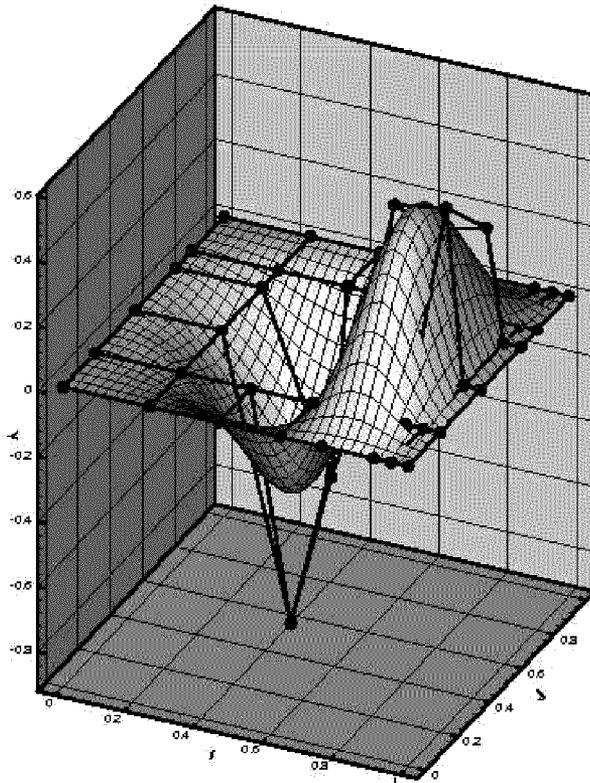


Fig. 5 An example of Bezier patch.

is constrained, and cannot vary of more than the 2.5% of its initial value. These limitations are necessary because the sonar must fit in the new bulb too.

The adopted optimiser is described in [5], [6]: it is a derivative-based optimiser, whose main algorithm is a Conjugate-Gradient (Polak-Ribiere). Geometry handling is performed by superimposing of a Bezier surface to the original one, as reported in fig. 4. A Bezier surface is controlled by a fixed number of control points, much less of the number of points of the computational grid. By using this approach, the control points of the Bezier surface are assumed as design variables of the optimization problem, and the shape of the PHF can easily be varied. In figure 5, a detail of a Bezier patch is reported. Control points (the black dots) at the external boundaries of the surface patch are fixed at zero in order to allow a smooth connection between the unmodified hull portion and the modified part. Indeed, if one row (or column) of

control points is fixed at zero on the boundary, the Bezier patch starts from zero, and the position of the grid points at that boundary is not modified. In the same way, if two rows of control points are fixed to zero, the Bezier surface starts from zero with zero tangent, and the modified shape is perfectly faired with the unmodified hull. As a consequence, a careful choice of the control points placement is necessary, in order to obtain a new producible geometry.

Gradient computation: RSM methodology

As stated before, the adopted optimiser is a derivative-based one: in this class of optimiser, a descent direction in the space of the design variables is searched using information derived from the local gradient of the objective function. After a descent direction is fixed, the optimal steplength along this direction is selected, looking at the obtained improvements on the objective function. After that, a new descent direction is searched again, as soon as an optimal condition (zero gradient of the objective function, very small improvement, maximum number of allowed iteration reached, etc.) is found.

The gradient of the objective function is usually computed by a central difference scheme: each design variable is varied, one at a time, from the actual value by $\pm \Delta\xi$, the objective functions F^+ and F^- in correspondence of $(\xi_i + \Delta\xi)$ and $(\xi_i - \Delta\xi)$ are computed, finally obtaining the gradient as $g_i = (F^+ - F^-)/(2 \Delta\xi)$.

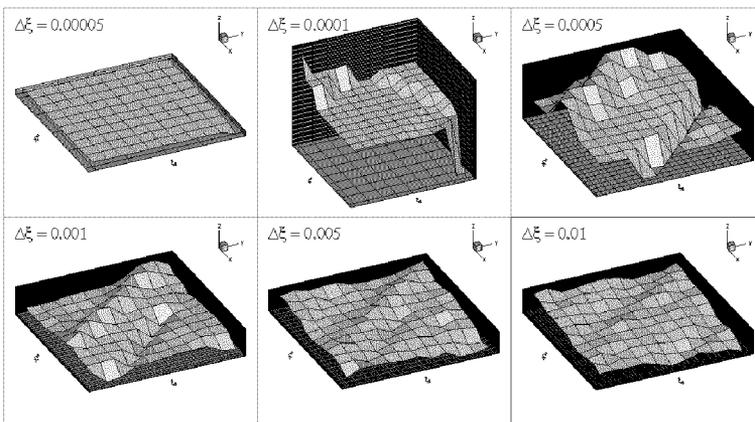


Fig. 6 Pitch motion as function of two design variables: effect of different step of investigation

An alternative approach to this strategy is to use a local approximation of the objective function with an analytical function. To construct this approximation model, some trial values of the objective function are computed (using the potential flow solver describe before) for geometries close to the PHF. The careful choice of this trial points, together with the construction of the approximating model, is performed by applying the Response Surface Methodology (RSM), described in [4]: it is based on the Design Of Experiments (DOE) theory.

The position of the training points is crucial for the correct approximation of the objective function. Usually the training points are placed on the vertex of a hypercube centred on the actual solution. The length of the edge is connected with the portion of the design variable space we are interested to investigate: since we are looking at the local behaviour of the objective function, the length of the edge should be very small, as well as the step $\Delta\xi$ adopted in the central differences scheme.

This method has the great advantage of applying an implicit smoothing of the noise usually introduced by the numerical computation of the objective function for small perturbations of the shape. These inaccuracies have strong effect on the optimization process, since wrong information on the local behaviour of the objective function cause a wrong descent direction: for this reason, often a premature stop of the optimization process is reported. Noise effects on the objective function are clearly reported in figs. 6, 7.

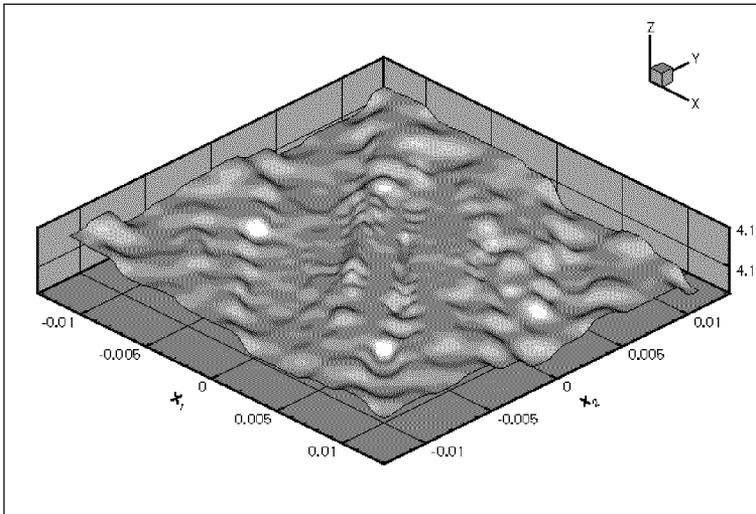


Fig. 7 Global rebuilding of the pitch motion as a function of two design variables.

In the case reported in figure 6 the peak of the pitch response of the ship in head seas is computed. The shape of the combatant has been parameterised by means of two design variables. The function has been computed on a 10 x 10 regular mesh, increasing the wideness of the investigated design variable area, each picture representing a different grid density, i.e. from top to bottom, the amplitude of the interval is increasing. If the mesh is too small (small investigated area), no variation at all is detected for the computed function, while sudden change in the objective functions are detected for some intermediate values of $\Delta\xi$. As a consequence, the step $\Delta\xi$ must be selected carefully: if it is too small, spikes should contribute to an erroneous gradient computation, while the local behaviour is loosed if a too large value is adopted.

In fig. 7, the complete reconstruction of the objective function is reported: here all the previously computed values are plotted together on a single surface. Numerical noise is here evident, and the investigated function suddenly changes his value. As a consequence, local gradient is very unstable, depending on the entity of the selected step $\Delta\xi$, and a smoothing strategy become essential if we need correct information on the local gradient without applying higher order methods for the gradient computation.

A comparison of the gradient components computed with the RSM technique and via a finite differences approach is reported on the following table. The bulb of the PHF was parameterised by using a Bezier patch with 4 design variables, and each gradient component is here presented, as from the two different methods. The high similarity of the exposed values confirms the goodness of the RSM implementation. As a consequence, the following optimization process will be performed by applying this last technique.

<i>Design variable</i>	<i>Finite differences</i>	<i>RSM technique</i>
1	0,791	0,792
2	0,523	0,519
3	0,281	0,282
4	0,149	0,156

Numerical results and experimental verification

Before start the optimization process, a verification of the capability of the adopted numerical solver have been verified on the original geometry: results are reported in fig. 2, that is comparable with the picture of experimental relief, reported in fig. 1. After this first verification, the previously defined optimization problem has been faced and solved, starting from the PHF.

In fig. 8, the numerical results are reported: blue line represents the wave profile along the hull, while the black lines on the models are the buttock lines, that is, the lines at constant y . Bold black lines are the block subdivisions for the numerical grid defining the model. The optimised model has a narrowed leading edge. Also the sonar dome is much narrower than the PHF, and it is curved in the upper part.

Numerical results are reported in fig. 9. The wave profile along the hull is reported for the original model, the PHF and the optimised model. In abscissa the longitudinal coordinate along the model is reported, non-dimensionalized by the model length, while in the abscissa the wave height (ship scale) is reported. Model is centered on the 0 value, lying in the interval $[-0.5 / 0.5]$. A strong reduction in the

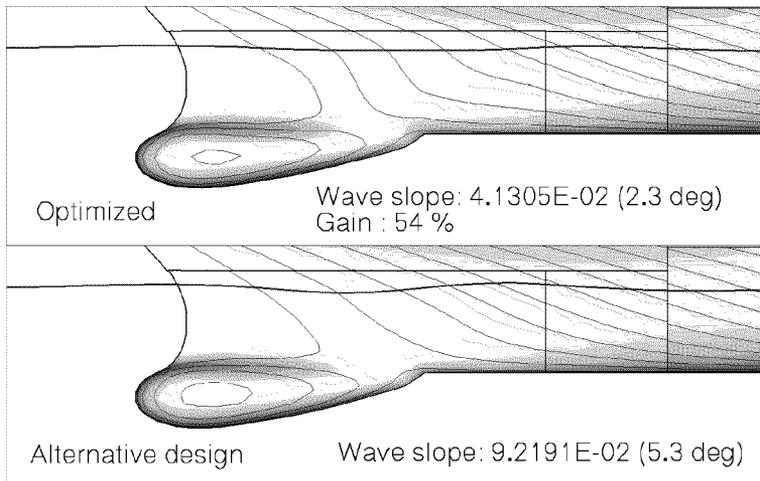


Fig. 8 Geometrical differences between the optimal hull shape and the alternative design. Contour lines of the lateral coordinate (y) are reported on the hull. Blue line is the wave profile along the hull.

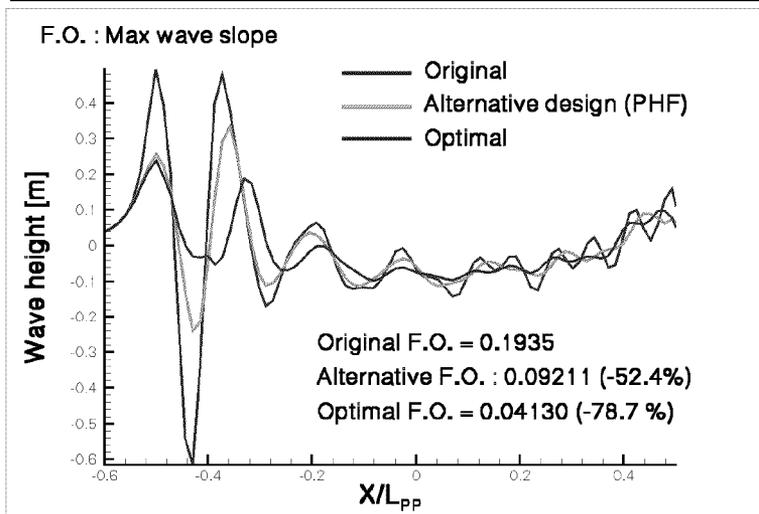


Fig. 9 Comparison of the wave elevation along the hull as computed by the numerical solver for the three hulls.

wave profile is predicted, and advantages are also reported in fig. 9.

After that, experimental tests have been conducted on the two new geometries. A quantitative estimation of the obtained results is deducible by the pictures in figs. 1, 3 and 10. Looking at the horizontal lines traced on the hull, for the original model the wave profile touch the line traced on the model numbered by 6, that means 6 meters from the keel line. Since the draught of the model is 4.6 meters, a wave of 1.4 meters is generated by the original hull. Looking at the PHF (fig. 3), the wave is placed in the nearby of the line at 5.5 meters, so the produced wave is 0.9 meters high, with a reduction of 0.5 meters on a wave of 1.4 meters, that means a gain of about 36%. Finally, the wave produced by the optimized model (fig. 10) touch the line placed at 5 meters on the model: a wave of 0.4 meters is produced by this geometry, and the corresponding gain is of 71% if computed with respect to the original model and of 56% with respect to the PHF. These results are exposed also in the following table.

<i>Bulb</i>	<i>Wave height</i>	<i>% gain (experimental)</i>	<i>% gain (numerical)</i>
Original	1,400	0,000	0,000
PHF	0,900	35,714	52,400
Optimized	0,400	71,429	78,800



Fig. 10 Experimental verification on the optimal hull shape in the same conditions and viewpoint of fig. 1

could be addressed to the strong limitations in shape modification together with the low optimizing speed. In fact, the form factor of the optimised hullform is very similar to the one of the PHF, due to the small allowed changes in shape: as a consequence, all the differences are addressed to the wave resistance, that is the lower part of total resistance at low speed, being the viscous and frictional part the greater ones: for this reason, a strong reduction on wave resistance component becomes a small variation on total resistance.

On contrast, while the total resistance at 12 knots is reduced, a small increase on the total resistance at the other speeds is obtained for the optimized model, as reported in fig. 11, because the flow characteristics are not controlled at the other speeds: as a consequence, the total resistance value at higher speeds is not guaranteed.

The gain on total resistance is very low at 12 knots (of about 1%) if compared with the strong reduction of the wave pattern: this

Conclusions

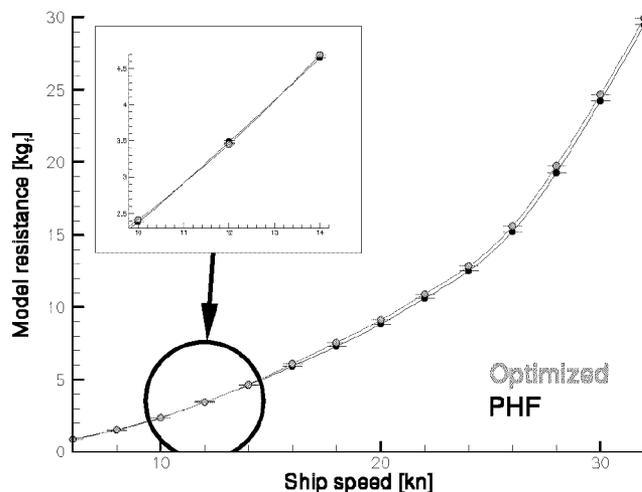


Fig. 11 Experimental value of the total resistance (model scale) for the optimised hull and the alternative design. Optimised hull reduce the total resistance only at the optimising speed.

The experimental results here exposed indicate how the numerical optimization techniques are useful in the design cycle. A further reduction of the objective functions has been achieved, even though starting from an improved hull form. Drawbacks could be avoided by defining a multidisciplinary (or multiobjective) optimization problem, in which more than a single objective function are considered together, trying to find a solution that is able to enhance the ship under more than a single standpoint: attempts in this application field are presently obtained [7].

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Paper #56

Discussor's Name: Professor Ramana Grandhi

Author's Name: D. Peri

- Q: 1) Is the sensitivity analysis completely analytical within the CFD code? What is the cost of CFD simulation alone compared to sensitivity analysis? Did you use adjoint variade method?
 2) Did you try to build RSM in the feasible set and then build Pareto curve on RSM?

A: 1) Yes, SA is fully integrated in the CFD code. The cost of SA is about 25% of the glow solution, but it depends from the number of design variables, becoming lower when the number of design variables increase. We use both direct and adjoint methods.
 2) Yes. It is what we are used to do.