Hydrodynamic Yacht Bulb Optimization by Embedding the Hull in a B-Spline Space

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Abstract. *A novel optimization method is presented where ship hull geometry is embedded in a B-Spline parallelepiped regardless of the specific approximation of the hull (panels, mesh, surfaces). The optimization procedure deforms the B-spline space while the B-Spline moves smoothly every pre-mapped hull point. Moreover, the final B-spline transformation can be applied on a different geometrical hull approximation to accommodate various hydrodynamic solver input requirements. The paper presents an example where the new method automatically converted a standard bulbous bow of a yacht into an inverted piercing bow. The numerical results for the original bulb were validated with model tests. The bulb performance improvement was evaluated with potential (v-SHALLO) and viscous flow (STAR-CCM+) solvers, which both show a 9% reduction of the total ship resistance at the design speed. The optimized bow shape can save energy and lower emissions.*

Keywords: Hydrodynamic optimization, ship hull, bulbous bow, B-spline, yacht bulb

Introduction

Hydrodynamic simulations are a common part of ship design. Ship hull geometry often needs to be optimized to achieve better performance [1]. Most hydrodynamic computer codes require a discrete approximation of the geometry. The geometry is subdivided into thousands of elements to serve the calculation needs. Hydrodynamic optimization of the ship hull, on the other hand, benefits from smooth gradual geometric changes. Parametric modification functions for the bow hull-form variation have been used [2] with parameters such as bulb height and bulb size. Mapping techniques [3] normally bring more flexibility to modify the shape while still keeping it smooth if the variations are performed in the longitudinal direction. The latter technique resembles hull changes by longitudinal shift and deformation of ship sections [4]. This paper proposes even more flexibility by allowing deformation of the mapped in a B-spline space hull in three orthogonal directions. The additional flexibility may allow generating unique hull shapes that may not be possible with other methods. The proposed technique will be demonstrated with a bow modification example, where the modified bulb significantly lowers the total resistance with larger hull displacement.

Hull Mapping

The first objective is to embed a ship hull in a B-spline box solid. The embedded hull can be approximated with bi-cubic surfaces (Fig. 1a), flat quadrilateral panels (Fig. 1b), or any other means. The grey box in Fig. 1 can be represented by a different number of control points. A relatively denser point grid (24 x 5) was used in this case, since only a small portion of the hull in the bulb area would be modified and thus, a greater resolution was needed locally. Any of these points can be used as optimization parameters, but only the two nearest to the bulb points (shown in red) were actually varied here. In other words, the optimization function had six parameters: 2 control points x 3 degrees of freedom. The objective function was the total hull resistance in calm water at a design speed of 16 knots (Fn=0.31).

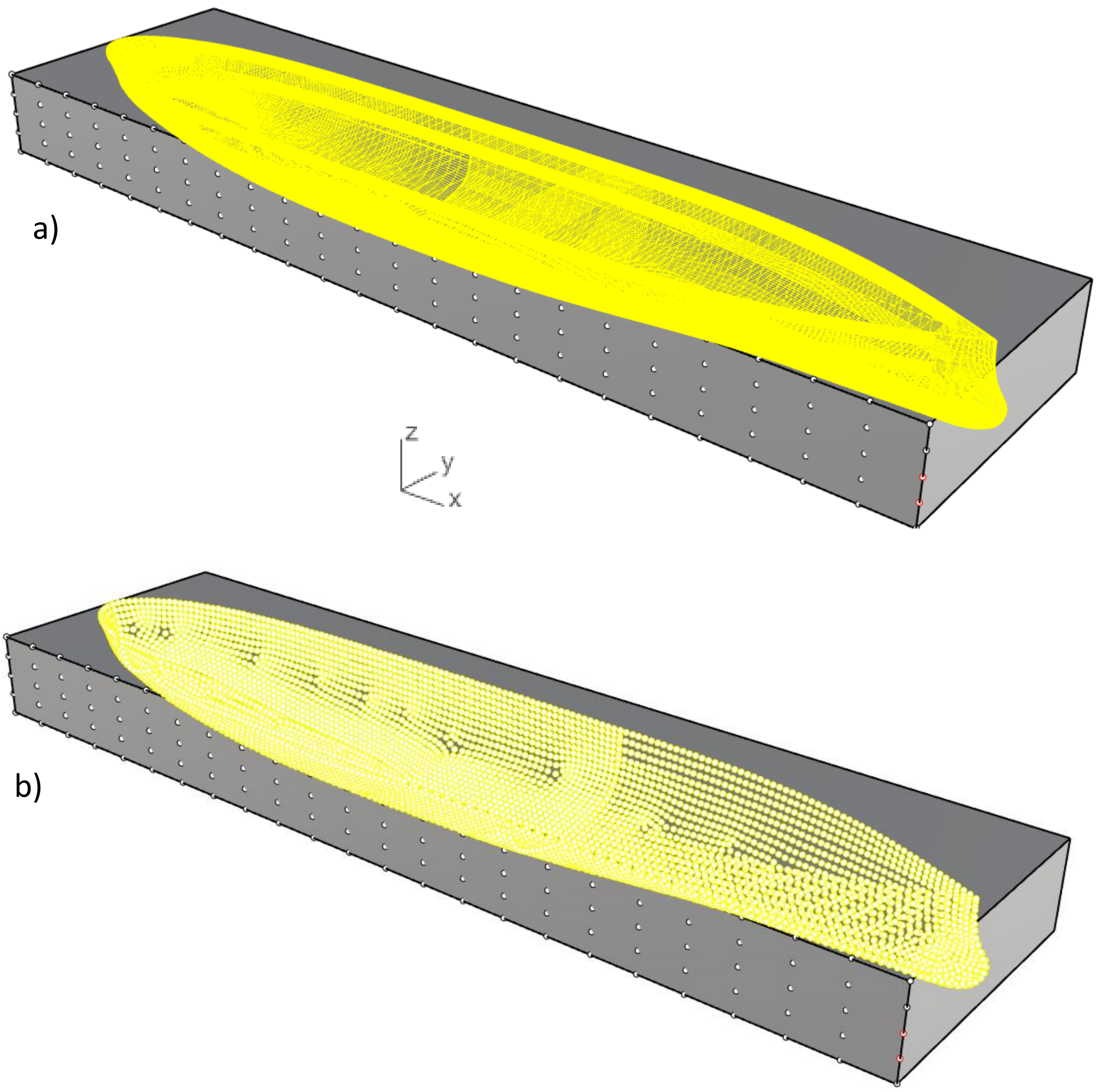

Figure 1: The embedded hull

The plane including the control points in Fig. 1 is approximated with a bi-cubic tensor product called B-spline surface [5]:

$$\bar{\boldsymbol{r}}(u,v) = \sum_{i=1}^{N_u} \sum_{j=1}^{N_v} \bar{\boldsymbol{d}}_{ij} B_i^3\,(u)\, B_j^3(v) \tag{1}$$

where $\overline{\boldsymbol{d}}_{ij}$ are the coordinates of the control points (B-spline vertices) shown in Fig. 1, $B_i^3(u)$ and $B_j^3(v)$ are known from the initial surface fitting basis functions of third degree, and N_u and N_v are the number of vertices in u and v directions, respectively. Note that the *Y*-coordinate $d_{ij}^{(2)}$ of the vertices is initially constant because it is a plane and will be normalized to be equal to 1.

The vertices $\overline{\boldsymbol{d}}_{ij}$ initially form a uniform grid, which simplifies the mapping of the hull because it uncouples the u and v directions. In other words, any point (x, y, z) point on the hull can be projected into the (u, v) space corresponding to the plane (1):

$$(x_k, y_k, z_k) => (u_k, v_k), \quad k = 1..N \tag{2}$$

where N is the number of the vertices of the quadrilateral panels or NURBS surfaces describing the hull. Once the (u_i, v_i) are associated with the hull points, the optimization procedure can start iteratively changing preselected control points $\overline{\boldsymbol{d}}_{ij}$, and the deformation of the box will result in a relatively smooth deformation of the embedded hull in the following way:

$$x(u_k, v_k) = \sum_{i=1}^{N_u} \sum_{j=1}^{N_v} d_{ij}^{(1)} B_i^3\,(u_k)\, B_j^3(v_k) \tag{3}$$

$$y(u_k, v_k) = y_k \sum_{i=1}^{N_u} \sum_{j=1}^{N_v} d_{ij}^{(2)} B_i^3\,(u_k)\, B_j^3(v_k) \tag{4}$$

$$z(u_k, v_k) = \sum_{i=1}^{N_u} \sum_{j=1}^{N_v} d_{ij}^{(3)} B_i^3\,(u_k)\, B_j^3(v_k) \tag{5}$$

for k=1..N. Note that formula (4) differs from (3) and (5). This is because the transformation acts as a scaling function in the transverse direction. Or the initial transformation preserves the original hull in the Y direction since it corresponds to multiplication by 1, which may change if the optimization procedure is allowed to change the Y coordinates of the control points $\overline{\boldsymbol{d}}_{ij}$. In that case, the control points in Fig. 1 would not form a plane anymore.

Hull optimization

The mapping of a yacht hull with a block coefficient of 0.55 was first executed according to (2) for 2963 quadrilateral panel yellow vertices in Fig. 1b. The choice was based on the fact that a potential flow solver normally can handle bulb optimization problems, and most of these solvers use flat panels for geometry. In this case, the nonlinear v-SHALLO solver [6] used 2751 panels for half of the hull.

The optimization process was automated by adding the three interacting software programs shown in Fig. 2. The optimal bulb solution stabilized after 107 iterations; see Fig. 3. The final position of the control points is given in Fig. 4. The optimization routine moved the points longitudinally almost to the upper 7% limit it was allowed to. It also brought the points closer vertically, which produced the sharp bulb shape shown in Fig. 5-7. The control points didn't move significantly in the transverse direction. The total resistance force decreased 9% for ship displacement increase of 1%.

The lower wave resistance is due to the lower bow wave seen in Fig. 8-9. The piercing bulb shape may be also helping with the viscous resistance component.

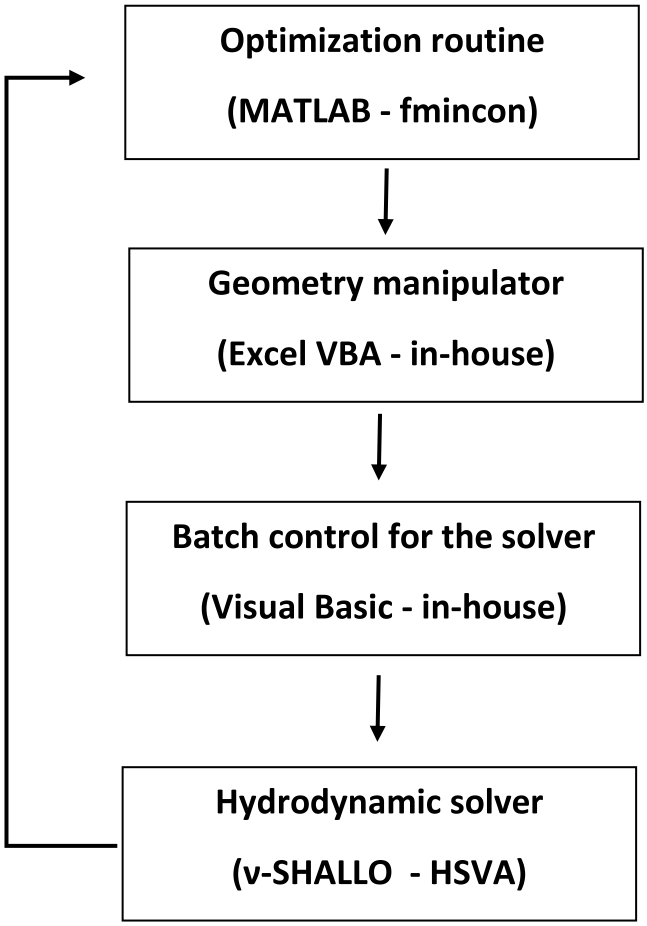

Figure 2: Four interacting programs used during the bulb optimization

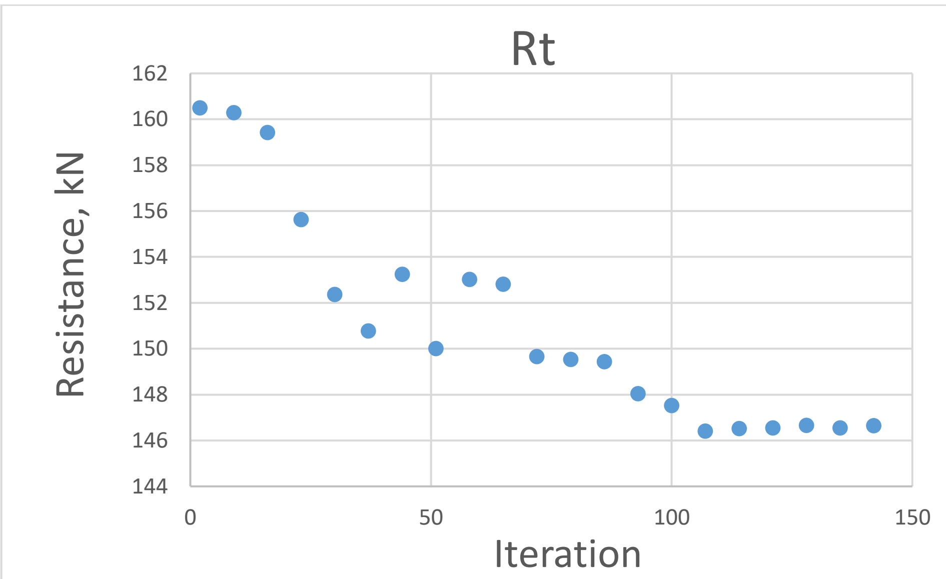

Figure 3: Optimization iterations

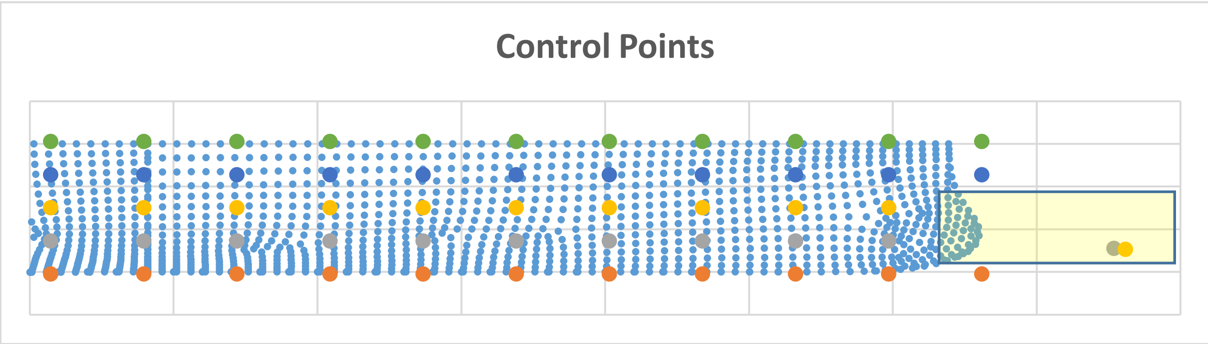

Figure 4: The final positions of the two variable control points after the optimization was completed

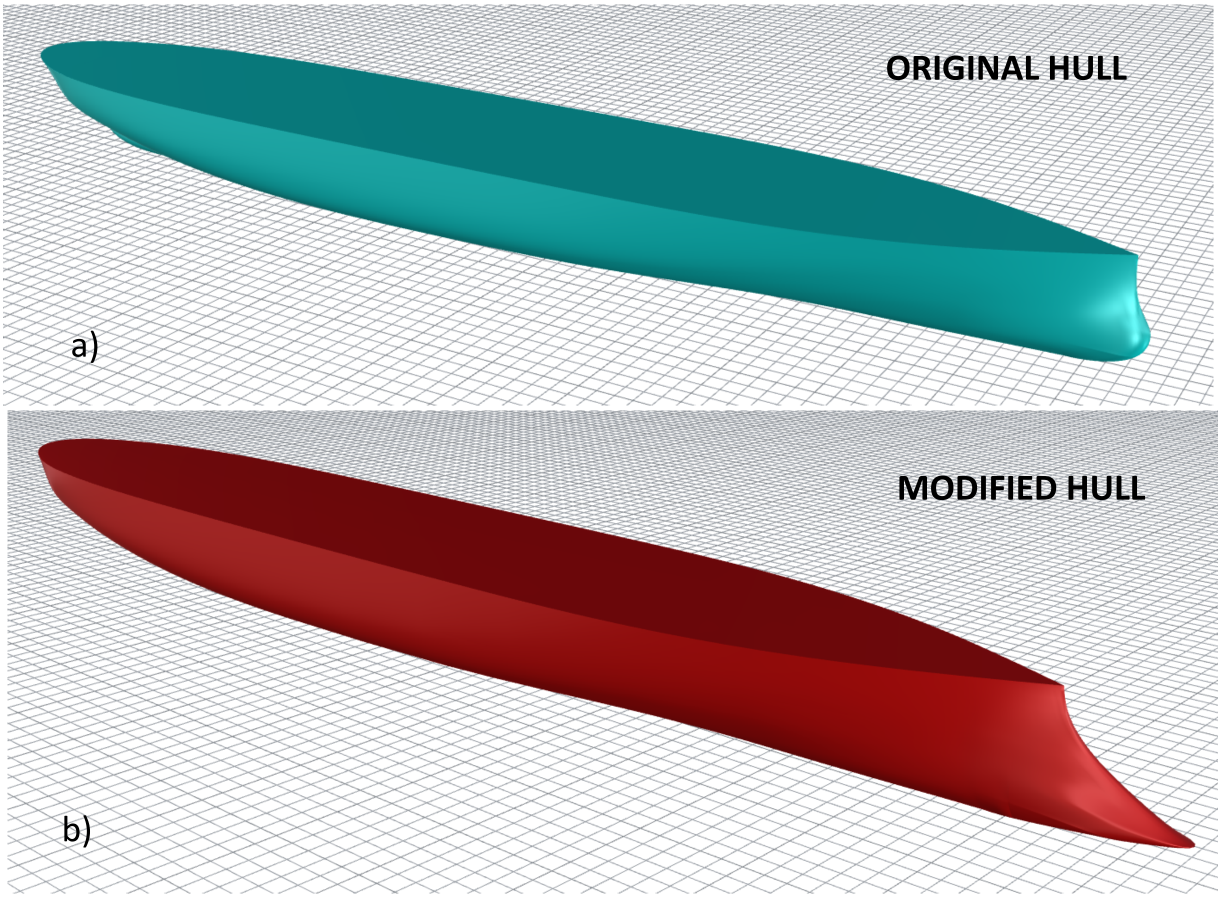

Figure 5: Comparison of the original and modified ship bow (displacement increase 1%)

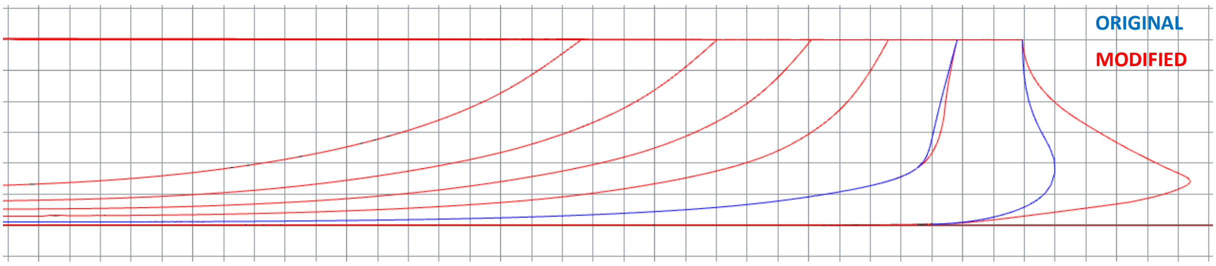

Figure 6: Buttocks comparison

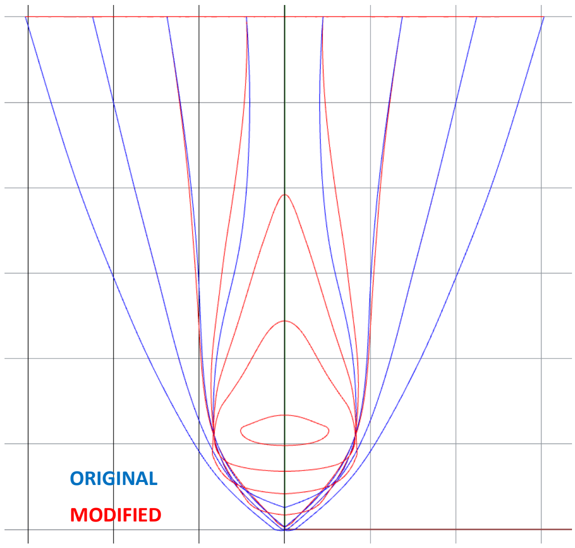

Figure 7: Sections comparison

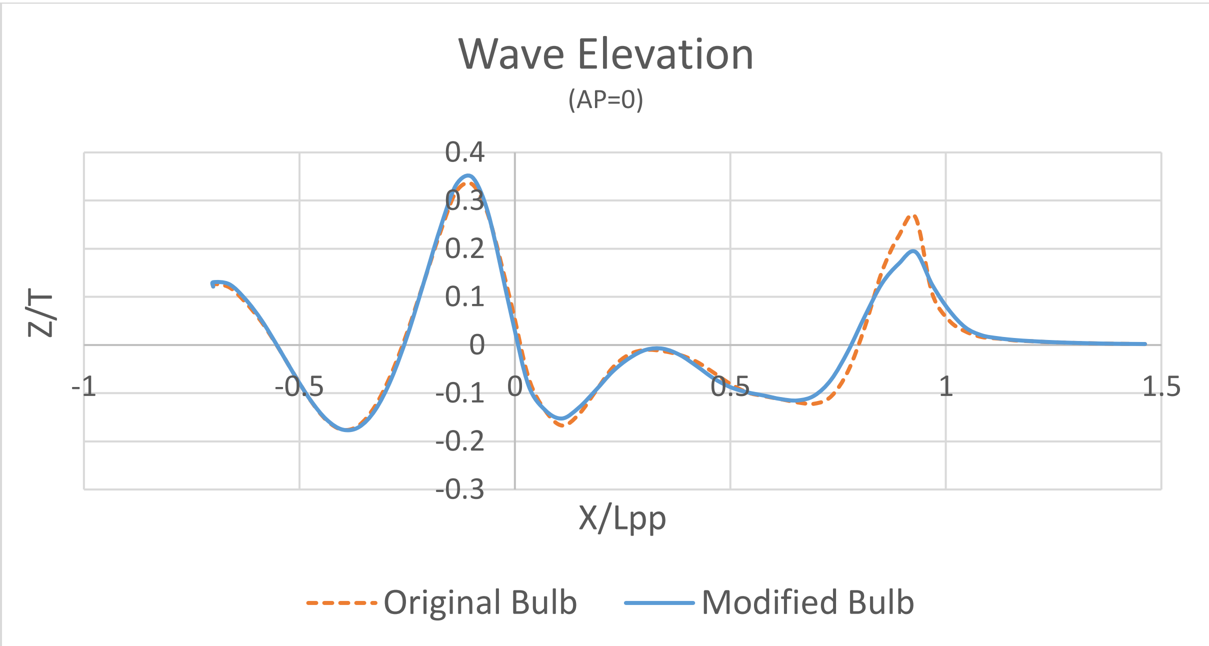

Figure 8: Wave elevation along the hull

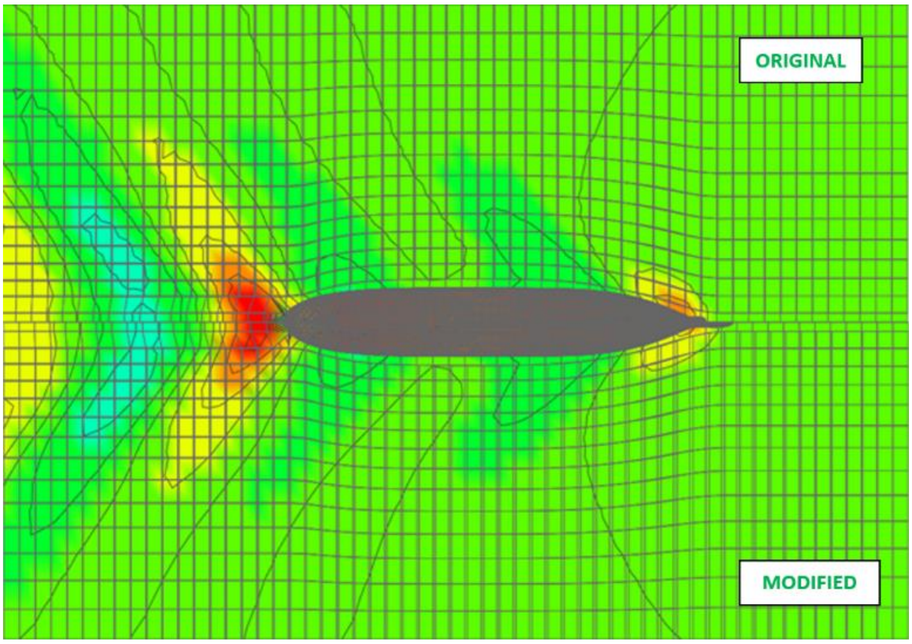

Figure 9: Wave pattern comparison, 16 knots, potential solver ()

The optimized solution was validated in two different ways.

1. The total resistance forces for the original and modified hulls at the design speed were also computed with STAR-CCM+ using the RANS k-ε turbulence model with 4,000,000-element mesh. The RANS solution also shows a 9% difference as the potential solver. The wave patterns are compared in Fig. 10 where the bow wave is visibly lower for the modified bow. Both numerical setups, including the meshes in Fig. 11, were generated with identical settings by using the commercially available "Estimating Hull Performance" (EHP™) add-on. The final B-spline geometry transformation applied to the quadrilateral panels was also applied to the NURBS surfaces (Fig. 1a and Fig. 5), and then supplied as input to the EHP™ mesher.
2. The potential and viscous flow solutions were compared with model test results for the original hull and showed good agreement; see Fig. 12.

The resistance then was compared for a range of speeds. The modified bulb shows superior performance for the entire range according to Fig.13Figure 13-14 and Table 1. Here, Cw is the wave resistance coefficient (calculated with the initial wetted surface); CT is the total resistance coefficient (calculated with the initial wetted surface); and Rt is the total resistance in kN. Note that ν-SHALLO is a fully non-linear, free-surface potential CFD method computing the inviscid flow around a ship hull at a free surface. Eight iterations were used for every non-linear free surface solution in the presented bulb optimization problem. The "viscous pressure force" is an estimate of the viscous forces which are likely to act on the aft-body of the ship hull due to the thicker boundary layer. Here a cut-off value for a maximum pressure coefficient Cp on the aft-body is used to determine the fraction of resistance due to viscous pressure. The simplification was validated in this case with the viscous STAR-CCM+ solver.

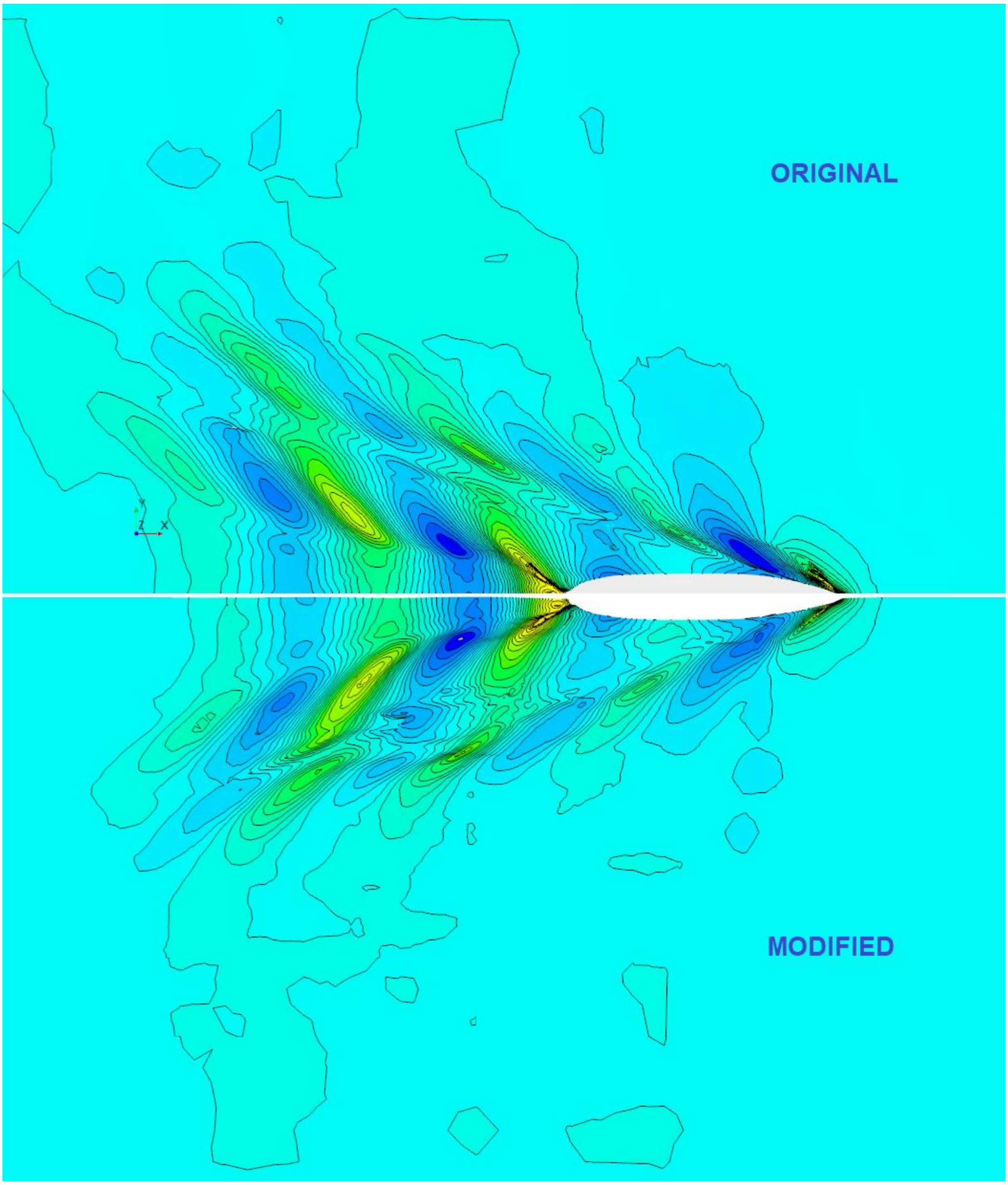

Figure 10: Wave pattern comparison, 16 knots, RANS solver (STAR-CCM+)

Figure 11: 3D mesh, 4 million elements, RANS solver

Table 1: Difference in resistance between the modified and original hulls

V	Delta		
knots	Rt	Cw	CT
10	-11%	-64%	-13%
11	-15%	-79%	-17%
12	-16%	-70%	-18%
13	-10%	-47%	-12%
14	-15%	-40%	-17%
15	-11%	-28%	-13%
16	-9%	-18%	-11%

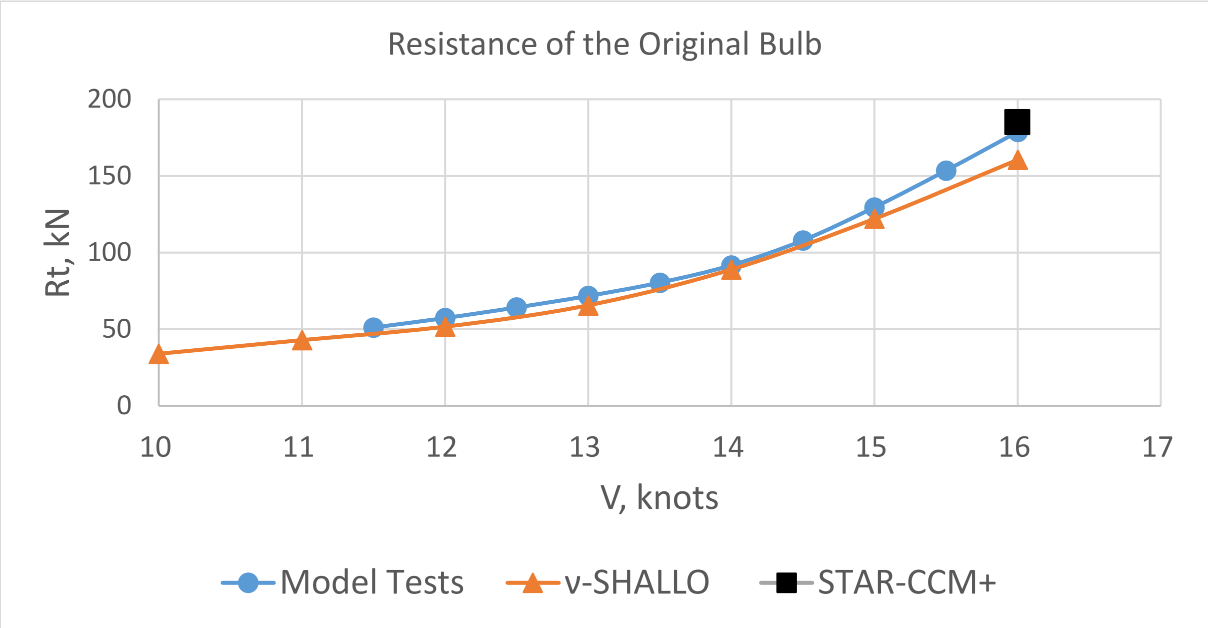

Figure 12: Validation of the numerical simulations for the original hull

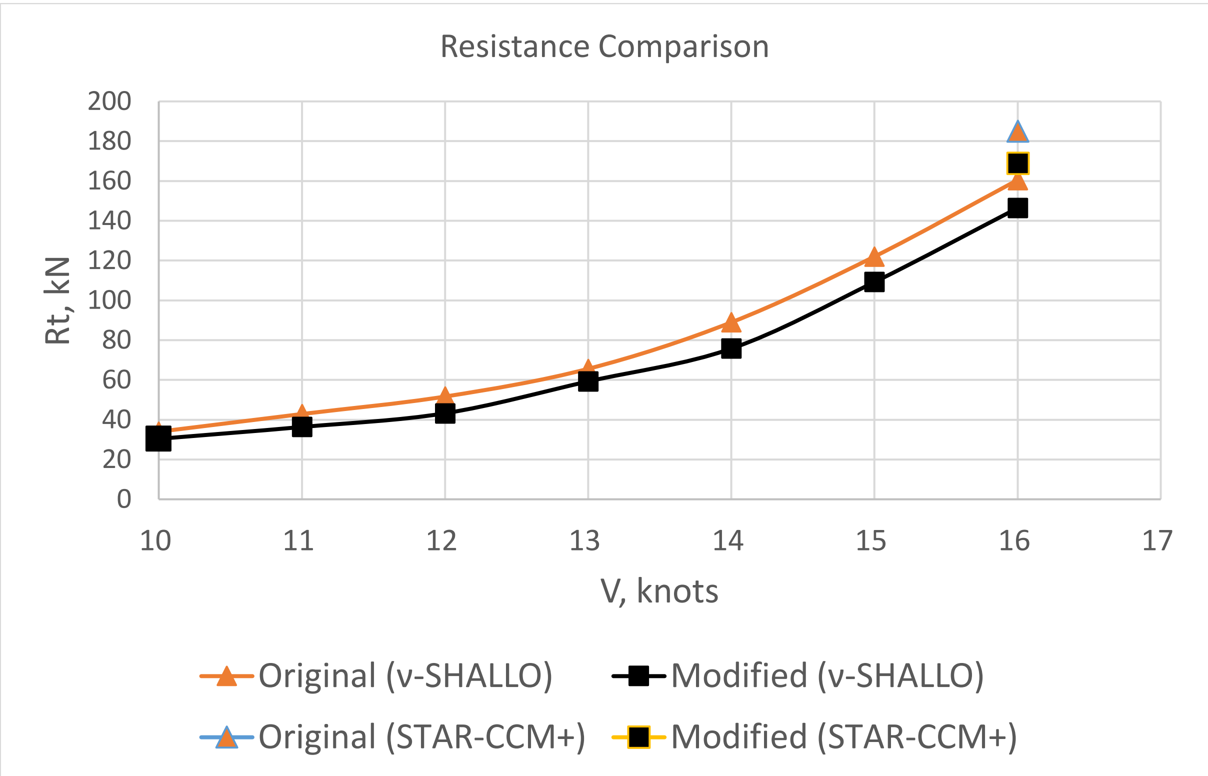

Figure 13: Resistance comparison for the original and modified bulbs

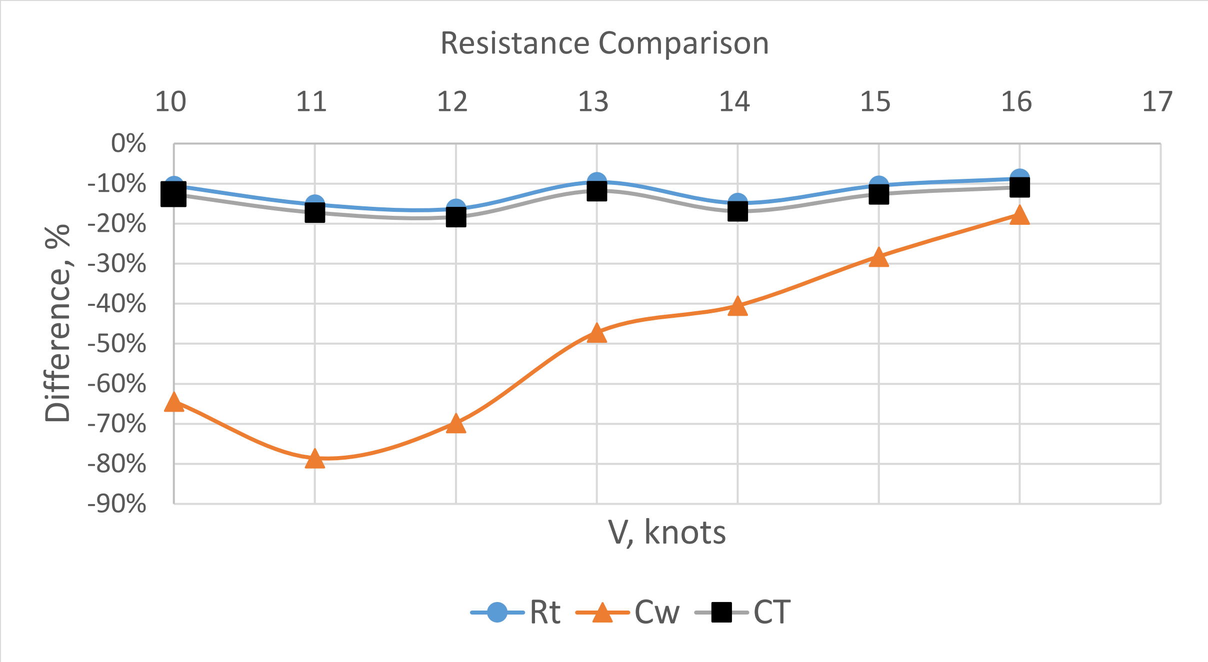

Figure 14: Resistance comparison for the original and modified bulbs

Conclusions

A practical technique for automated ship hull optimization is presented. The proposed geometry manipulation approach has the advantages to be flexible, intuitive, geometry independent and producing smooth changes to the hull form. The geometric independence can tailor inputs for various hydrodynamic solvers. The intuitive nature of the B-spline control points allows easy manual manipulation of the hull form. It also simplifies the work of the optimization routine, where having all parameters at the same scale is generally advantageous. The flexibility of the method led to the automatic generation of a new piercing bulb shape, which may not be possible with other common parametric approaches.

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