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A new concept for design of the shape ship stern

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Abstract

The paper presents an original stern shapes design which obtaining a good distribution of the ship wake able to reduce the drag. The paper begins to present the problems directly and reversely, physical mathematical shaping and the numerical implementation (including the precision of numerical approach). For this purpose, the imagining of a current tube is suggested, with increasing variable cylindrical sections, which starts from the disk in front of the propeller, extends towards the prow, very close to the cylindrical area and which includes the entire stern section of a classic hull having practiced cross corrugated sections). Certainly, the dynamics of a cavity propeller depends on the work environment system. The flow field around a propeller mounted on the ship is very different to the one that a propeller develops when tested in free water or in a section of a cavitation tunnel. A propeller with a very performance in free water may not be right for a stern shape of a hull of the given ship. For this reason, the ship wake distribution in the propeller disk plan represents a key factor for a ship design. The study tries to draw attention and briefly focuses on ships hull’s stern flows in the light of two absolutely strict original ideas (concepts) in ship hydrodynamics, belonging to the author: 1.a new stern hydrodynamic concept (NSHC), with radial crenellated-corrugated sections 2. using of an inverse piezoelectric effect [(electric current→high-frequency power generator→ piezoelectric driver made of certain ceramic material, which induces an elliptical vibratory movement (high frequency over 20 kHz), into the elastic side plates (15 mm thickness) in the streamlines direction (of the external flowing water)], able to reduce the total forward resistance. Resuming, it can be concluded that the new concept of stern shape proposed as well as the reverse mathematical problem presented above for its optimization, based on the Levenberg-Marquardt algorithm seem to be reasonable. Finally, the most important, until now, proved result, is the reducing of propeller cavitation (working in the simulated nominal wake of the hull using the new shape stern.

Keywords: vessel wake, propeller cavitation, drag, stern shape, cavitation tunnel, ultrasonic vibrator.

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1. Introduction

Always, but especially in the contemporary conditions of modern stern shapes appearance (more and more complex), the improvement of propulsion performances had represented and still represents a particularly important problem for the researchers from the naval hydrodynamics field and not only. The reason of this remarkable interest is due to the fact that a good distribution of the ship wake from the upstream plan, parallel with the propeller, can lead to the increase of the propulsion capability and also to the reduction of the propeller cavitation. In its turn, the reduction of the propeller cavitation has as an extremely positive consequence, the decrease of the stern structure vibrations and noises level.

Obtaining a good distribution of the ship wake is an objective of all naval architects. In addition, the global stability of the hull improvement by using a stern and a bow with a certain architecture (more adequate) could be considered as extremely beneficial.

The authors consider interesting the construction of a new mathematical model, uni-dimensional flow tube, which includes the new stern effects on the propeller.

Taking into account the theory of the current tube and the Bernoulli effect, we can appreciate (consider) that the 3D spectrum of the flow generated around and in the exterior of a classic hull stern having practiced cross corrugated sections can be substantially improved by architectural optimization in terms of unification (equalization) of the axle velocities in the anterior plan of the closest proximity of the propeller. The number of the corrugated teeth and their heights will be improved by direct numerical experiments. For every section, the size of the pace between teeth (the distance between two consecutive crests) decreases on the perimeter, from the diametric plan toward the borders. The maximum heights (amplitudes) of the corrugated teeth will be reached progressively, respectively longitudinally in front of the propeller and crosswise in the diametric plan.

The directions of the longitudinal crests and teeth bases corrugated sections, which start immediately after the cylindrical zone, will be those of the stern natural current lines (which can be established experimentally by a paint flow test) in order to avoid the appearance of whirlpools and for obtaining a minimum resistance to motion.

2 The Mathematical model

2.1 Numerical description of stern shapes by the B-spline method

Usually, in the naval field, there are two methods used for defining 3D surfaces: Bezier method and B - spline method. The B-spline curves represent a generalization of the Bezier curves. The main difficulties of the Bezier method (curves) are:

-the numerical instability for a higher number of control points;

-the global change of the curve shape by the movement (moving) of a single control point.

For these reasons, in the present paper, as method for numerical defining and manipulation of stern surfaces, the B-spline technique will be used. The surface is generated by a network of parametrical curves which intersect. The method will be implemented on a computer with interactive graphic facilities for designing and smoothing (fairing) of the surface. Using a smaller number of fixed points (of control), the defining will be realized using the computer's screen interactively. An exact link between these fixed points (of control) and the surface defining is established by narrowing the longitudinal parametrical curves at water lines, thus making possible the manipulation of the surface in smooth projections on the screen. The surface defined by the B-spline method does not require any kind of specific geometric restrictions, the joint lines, the stern mirrors, discontinuities or propellers' hubs being modeling elements.

Let's consider a parametrical B-spline surface given by:

$$Q(u,w)=\sum_{i=1}^{n-1}\sum_{j=1}^{m-1}B_{i,j}N_{i,k}(u)M_{j,1}(w) \qquad (1)$$

$$2\le k\le n+1;\ 2\le l\le m+1$$

$$N_{i,1}=\begin{cases}1 & if - x_i\le u\le x_{i+1}\\ 0 & \text{otherwise}\end{cases}$$

$$N_{i,k}(u)=\frac{(u-x_i)N_{i,k-1}(u)}{x_{i+k-1}-x_i}+\frac{(x_{i+k}-u)N_{i+1,k-1}(u)}{x_{i+k}-x_{i+1}} \qquad (2a)$$

and

$$M_{j,l}=\begin{cases}1 & if......y_j\le w\le y_{j+1}\\ 0 & otherwise\end{cases}$$

$$M_{j,l}(w)=\frac{(w-y_j)M_{j,l-1}(w)}{y_{j+l-1}-y_j}+\frac{(y_{j+l}-w)M_{j+1,l-1}(w)}{y_{j+1}-x_{j+1}} \qquad (2b)$$

in which:

x_i, y_i – the elements of a uniform bend vector;

k, l – the order of B-spline surface in *u* and *w* directions;

n, *m* – the numbers of polygonal network points minus one, in *u* and *w* directions;

$Q(u,w)$ – data (coordinates) of surface points;

N, M – B-spline basic functions (that can be determined from the uniform bend vector and the parametrical values of *u* and *w*);

$B_{i,j}$ – points of the requested polygonal network (control points); if $B_{i,j}$ are given, the coordinates of surface points $Q(u,w)$ can be calculated from the equation (1).

Obtaining the B-spline surface:

- for each known surface point, the equation (1) leads to a linear equation in unknown $B_{i,j}$; similarly for all data (coordinates) of the surface points. In matrix notation:

$$[Q]=[C][B] \qquad (3)$$

- because for any arbitrary rectangular topological surface point *r x s*, [C] is not normally square, a solution can be obtained only in a certain average sense:

$$[B]=\left[[C]^T[C]\right]^{-1}[C]^T[Q] \qquad (4)$$

2.2 Reverse problem (re-designing the geometry of the stern shape)

In the reverse problem, the stern geometry is regarded as unknown and dominated by a number (by a set) of control points. The dimensionless axial component of velocity, U_{x_i} on the propeller disk plan is calculated by interpolation of the RANS results (direct problem) in the circumferential directions (θ) and radial (*r*) so that it can be expressed as $U_x(r_i,\theta_i)$. If n represents the number of sample points from the propeller disk plan, we can make the notation:

$U_x(r_i,\theta_i) = U_{x_i}$, i = 1,...,n;

these being said, the reverse problem of redesigning the geometry of stern shape can be formulated as follows: „Using the mentioned wanted axial ship wake coefficients, U_{x_i} you redesign the new geometry of the stern”. The solution is obtained by minimizing the following function:

$$f\left[\hat{\Omega}(\hat{B})\right]=\sum_{i=1}^{I}\left[\hat{U}(\hat{B}_j)-U_{x_i}\right]^2=\Delta^T\Delta \qquad (5)$$

j=1,….,J ; where:
U_{x_i} – the axial velocity coefficients (estimated or calculated) from (r_i, θ_i).
These quantities are obtained from the direct problem for a pre-estimated stern geometry $\hat{\Omega}(\hat{B})$;
I - the number of the points in which the ship wake is measured;
J- the number of control points which govern the stern geometry, $J = (n+1)x(m+1)$;
^ - estimated quantities.

2.3 Levenberg-Marquardt algorithm

From the ideas mentioned previously we deduct that the equation (5) can be minimized compared to the estimated B$_j$ parameters, to obtain:

$$\frac{f\left[\hat{\Omega}(\hat{B})\right]}{\partial B_j} = \sum_{i=1}^{I}\left[\frac{\partial \hat{U}_{x_i}}{\partial B_j}\right]\left[\hat{U}_{x_i} - U_{x_i}\right] = 0 \qquad \text{j=1,….,J;} \quad I \geq J \tag{6}$$

If I≤J the solutions of the reverse problem are impossible to calculate because the equations system that will be obtained is undetermined.

The equation (6) is linearized by the development of the function $\hat{U}_{x_i}(B_j)$ in Taylor series and retaining only the first order terms. A damping parameter λ is added to the resulting expression for the convergence improvement, leading to the Levenberg-Marquardt method given by the relation:

$$(F + \lambda^n \cdot I)\cdot \Delta B = D \tag{7a}$$

where:

$$F = \Psi^T \Psi \tag{7b}$$

$$D = \Psi^T \Delta \tag{7c}$$

$$\Delta B = B^{n+1} - B^n \tag{7d}$$

n - iteration index;*T* - transposed matrix
I - unit matrix; Ψ - Jacobian matrix defined by the relation:

$$\Psi = \frac{\partial U_x}{\partial B^T} \tag{8}$$

The Jacobian matrix defined in the relation (8) is determined by the disturbance of every unknown B_j parameter at a given moment and calculating the change that results for the axial velocity coefficients from the direct problem solution.

We now write the equation (7a) in an adequate form for the iterative calculation as follows:

$$B^{n+1} = B^n + (\Psi^T\Psi + \lambda^n I)^{-1}\Psi^T(\hat{U}_x - U_x) \tag{9}$$

2.4 Numerical method

Being given an initial arbitrary solution (pre-estimated) for the researched set of parameters – control points B (obtained by using the geometry of the stern shape and the approximation of the B-spline surface), the Marquardt numerical method (algorithm) is the following:

-Solving the direct problem in order to obtain the estimated (or calculated) axial ship wake $\hat{U}_x$;

-The construction of Jacobian matrix according to the equation (8);

-The update of B from equation (9);

-The verification of the stop criteria; if this is not satisfied, the procedure is resumed. Due to the fact that the objective function is not located on the hull surface, the correlation between the objective function and the control points is not very sensible. In order to avoid the possibility of numerical divergence during the process of flow simulation, it is better to select an adequate optimization criteria in a preliminary status.

3 Theoretical and experimental analysis

3.1 Theoretical analysis

In real conditions, a propeller is fitted behind the ships (models) hull's stern, working in a non-uniform water stream, which has been disturbed by the ship's hull during its forward motion. The ship's moving hull carries with it a certain mass of the surrounding water forming a region in which there is a rapid change in velocity well-known under the name of **boundary layer**. The propeller being placed behind the ship's hull stern, there is in the ship's body trail. As a consequence (even considering the average velocity), the velocity of water particles relative to the propeller disk is no longer (both neither in magnitude and nor in direction), equal to the velocity of advance of the propeller relative to still water. This trail, in which there is a difference between the ship speed and the speed of the water particles relative to the ship is also termed **wake**. Generally speaking, the wake is a zone not investigable theoretically (analytically), due to very complex, aleatory flow character within it. In ship's propeller theory, a distinctive importance is having only the incipient part of the trail (wake), located immediately in the front of the propeller disk plane. The movement from this zone is called wake movement or simply wake. The wake movement can be investigated or in the presence or in the absence of the propeller, when is taking the attribute of the effective wake or the nominal wake, respectively. However, the wake movement of interest is only that from the plane where the propeller follows to be situated. The flow's average velocity from that plane is termed wake speed v_W, and is in general smaller then ship's speed v_S, relative to infinite upstream water. If the water is moving in the same direction as the ship, the wake is said to be positive. Then for adimensionalization, the precedent relation can be divided by either v_W or v_S leading to two wake factors:

$$\text{-Froude wake factor} = w_F = (v_S - v_W)/v_W \tag{10}$$

$$\text{-Taylor wake factor} = w = (v_S - v_W)/v_S \tag{11}$$

Besides, this general effect of the ship's hull, there will be local perturbations due to the shaft, shaft modeling or shaft brackets and other appendages. These effects combined lead to the so called relative rotative efficiency (RRE), defined by: RRE = h_R = efficiency the ship hull**/**efficiency of propeller in open water (at speed v_W); Always, but especially in present circumstances, propeller cavitation reducing, overall propulsive efficiency and stability improving, represent important challenges for researchers from ship hydrodynamics field and not only. As already mentioned previously, the dynamics of a cavitating propeller depends on the system environment in which it is operating: such as, the flow field within a propeller mounted behind of a ship hull is very different from that one in an open water test or in a section of a cavitation tunnel. Thus, a propeller that is very efficient in open water can not be suited for a certain kind of stern shape architecture. For this reason, the wake distribution in the propeller disk plane represents a key element for designing of a ship hull stern form. A uniform wake distribution from an immediately upstream propeller parallel plane disk can lead to the formation of propeller cavitation decreasing (having as indirect consequence on the noise and vibration level induced on board and in the hull stern structure, lowering), the propulsive efficiency increasing (for minimum energetic consumptions obtaining). Therefore, obtaining of a good nominal wake distribution is an important objective of all naval architects. In addition, the global–directional hydrodynamic stability improving by using a special kind of stern having certain architecture (more appropriate), can not be but favourable. Of propeller behind Wake = $v_S - v_W$.

3.2 Experimental analysis

We have proposed (intuitively, based on experience), a new stern hydrodynamic concept of streamline tube type, (having quasi-cylindrical increasing sections), which starts from front propeller disk and stretches until hull cylindrical region (Figure 1).

In devising of this new design concept, the author referred (as a supplementary basic background) to two very well known and simple existing theories:

- the streamline tube theory (the water particles axial velocities distribution at entrance in the propeller disk can be configured favourably - homogenized-by comprising the radial corrugated stern sections in a stream tube that also comprises the propeller disk);

- the Bernoulli Effect (increasing of water particles axial velocities in the regions within which the water pressure is decreased). Taking into account the streamline tube theory and the Bernoulli effect, we can estimate that **the 3D spectrum** of flow generated around and outside of a classical stern hull having practiced transversal corrugated stern sections can be substantially improved by an architectural optimization in the sense of axial velocities from a propulsion propeller immediate front plane uniformization (Figure 2).

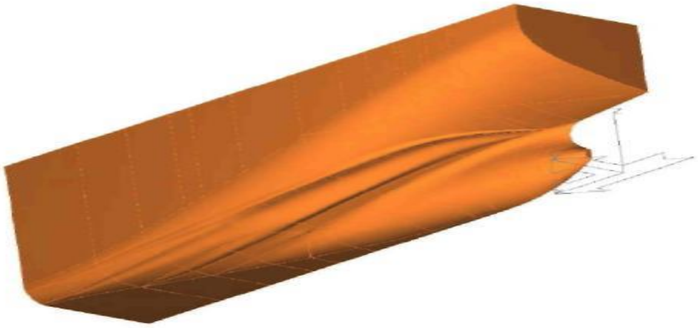

Figure 1. A new stern hydrodynamic concept of streamline tube type

The directions of the crenellated-corrugated sections teeth crests and troughs longitudinal curved lines, will be those of the stern natural streamlines (which can be established experimentally in a flow visualization test) for vortices turning up avoiding and for a minimum forward resistance obtaining.

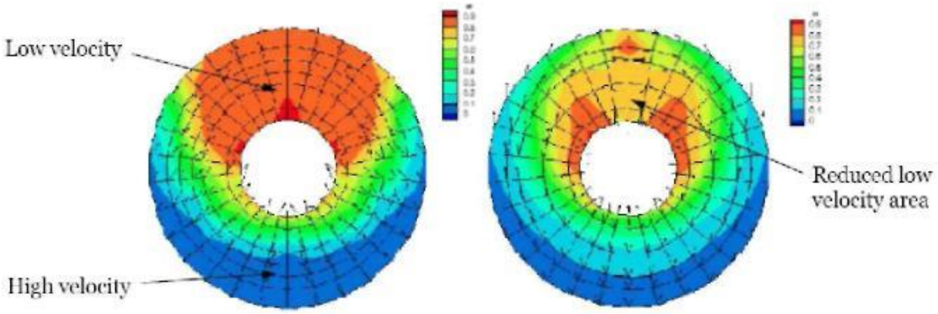

Figure 2. Comparison between experimental wake obtained for the model with initial stern shape design (left) and for the model with modified stern shape in conformity with the new concept design (right).

Finally, the most important, until now, proved result, is the reducing of propeller cavitation (working in the simulated nominal wake of the hull using the new stern hydrodynamic concept, Figure 3).

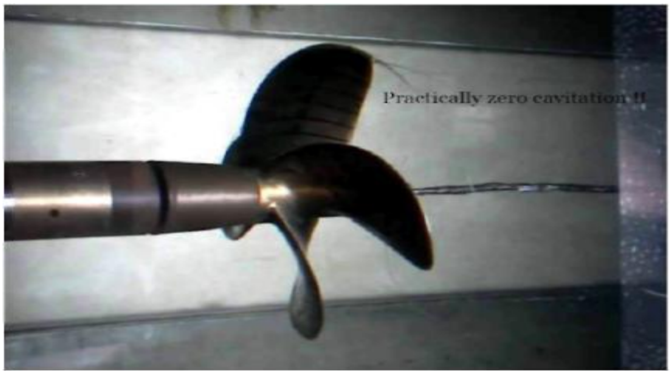

Figure 3.
Simulated nominal wake testing, in 850x850 mm section of the cavitation tunnel at 25 rps rotative speed (it can be remarked lack of cavitation).

Unfortunately, this cavitation decreasing (lack of cavitation) is associated with a total forward resistance (of the ship) increasing (approximately 4-5%) due to initiation and movement of some multiple increased vortices (Figure 4), resulted from the separation (although a low one – Figure 5) of the boundary layer (destruction of an important part of fluid mechanical energy, pressure decreasing on the down stream part of the ship stern body, etc.).

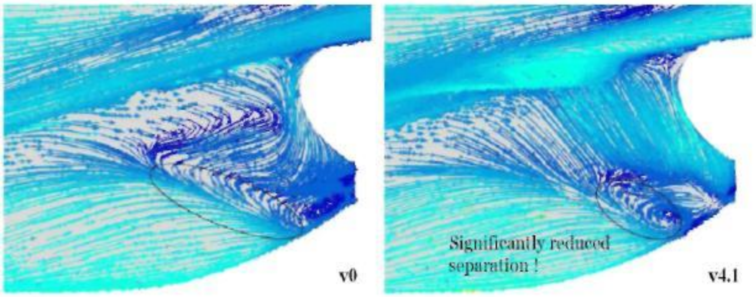

Figure 4.Vortex initiation and separation – FLUENT 6.3
(left - the model with initial stern shape design simple vortex; right- the model with modified stern shape in conformity with the new concept design- multiple vortices)

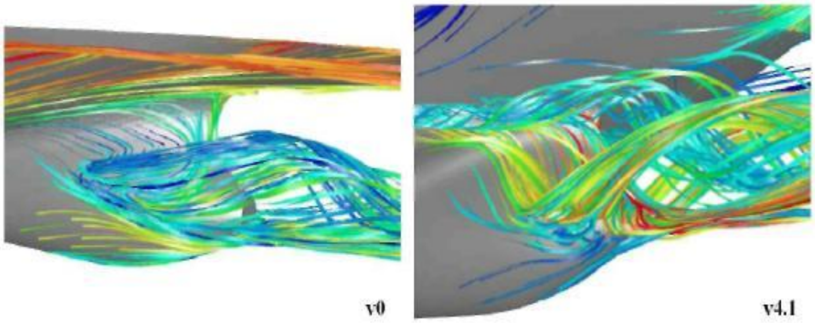

Figure 5. Limit streamlines on stern surface- FLUENT 6.3
(left - the model with initial stern shape design; right - the model with modified stern shape inconformity with the new concept design).

Therefore, it would be necessary (a much more) reducing or even complete separation and multiple vortices phenomena (within the turbulent boundary layer) avoiding. In this direction I thought that I should try to use the inverse piezoelectric effect (electric current→ high-frequency generator → piezoelectric driver made of certain ceramic material – Figure 6), which induces an elliptical vibratory movement (high frequency over 20 kHz), into the elastic side plates (15 mm thickness) in the streamlines direction (of the external flowing water).

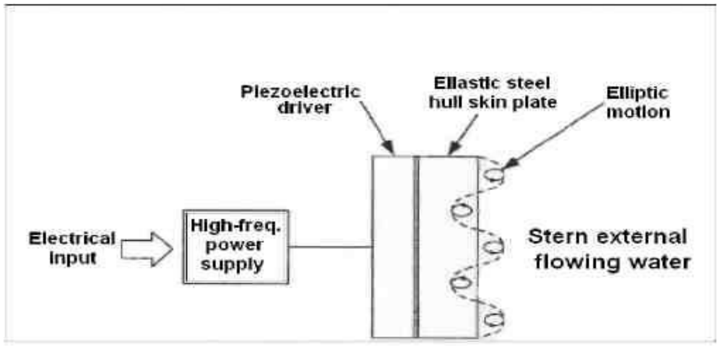

Figure 6. Principle scheme of an ultrasonic vibrator

Piezoelectricity is the ability of crystals and certain ceramic materials to generate a voltage in response to an applied mechanical stress. Piezoelectric effect was discovered by Pierre and Jacques Curie in 1880.

The basic principle would be the following: certain piezoelectric ceramic materials can be used to convert electrical energy into mechanical energy in the form of vibrations of an elastic body (ship hull stern plates), whose surface points perform an linear elliptic motion (in the streamlines direction of the external).

Water particles (from within the ship hull stern turbulent boundary layer – Figure 7), are pressed against vibrating steel plates reducing the interface (hull - water), skin friction drag.

It is hoped that such a combination of devices can reduce ship forward resistance due to hull skin-water friction reduction by controlling the inside turbulent boundary layer flowcharacteristics.

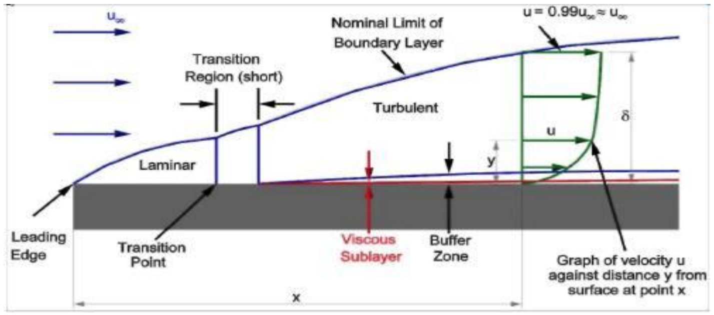

Figure 7. Boundary-layer flow regions

I consider as interesting the realization of a:

- parameterized geometrical model

streamline tube type, (including the effects of new stern design having quasi-cylindrical increasing radial crenellated-corrugated sections on inside propeller flow);

- design sensitivity analysis of the new stern fields generated.

In these cases different geometries (as necessary form, width and depth, along hull distances, for flow separation avoiding), should be studied theoretically, numerically and experimentally. Design sensitivity analysis consists in determining derivatives of a system's response with respect to its design parameters x_i. In the context of design optimization (of the new hydrodynamic stern concept proposed), the response is expressed in terms of objective and constraint functions, and accordingly the

$$V_f = \frac{df}{dx_1} + \frac{df}{d\gamma}\left[\frac{d\gamma}{dx_1}\right] - \frac{df}{d\phi}\left[\frac{d\varphi}{dx_1}\right] \tag{12}$$

After the determination of these flow field sensitivities, it is a matter of straight forward calculus to compute the design sensitivities:

f(x_i) – problem function (typically identical with objective and constraints function);

x_i – design parameters;

γ(x_i) – geometrical quantities;

Ø(x_i) – vector containing unknown flow variables (velocities, static pressure, possibly turbulence modeling quantities), determined by the governing equations).

Obviously, both geometry and flow are implicitly controlled by the design parameters through hull stern surface parameterization, mesh generation and flow analysis.

4. Conclusion

Resuming, it can be concluded that the new concept of stern shape proposed as well as the reverse mathematical problem presented above for its optimization, based on the Levenberg-Marquardt algorithm seem to be reasonable. Finally, the most important, until now, proved result, is the reducing of propeller cavitation (working in the simulated nominal wake of the hull using the new shape stern.

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