TRADE-OFF ANALYSIS REPORT

HIGH SPEED TRIMARAN HYDRODYNAMIC DESIGN

Submitted to:

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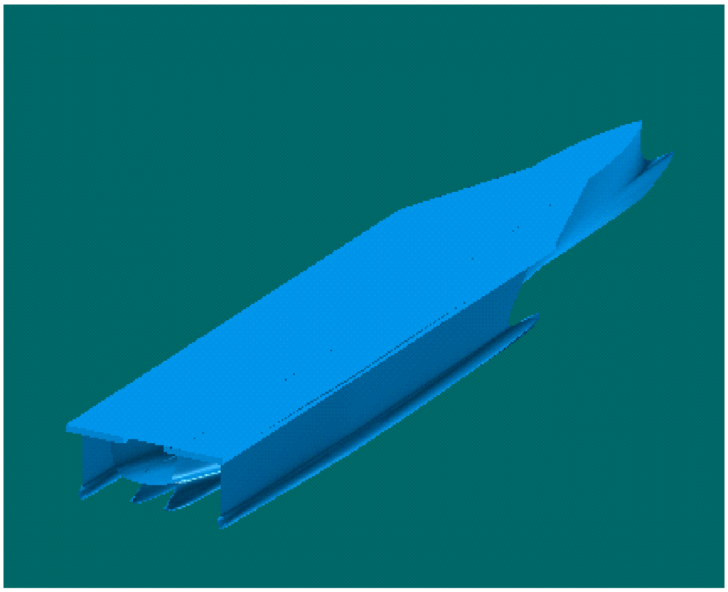
High Speed Trimaran Technology Development

Trade-Off Analysis and HST Hydrodynamic Design
Drag Reduction and Hull-Waterjet Interaction Analysis



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INTRODUCTION

This task conducts design trade-off studies for large HST design, including propulsion arrangement and hull-waterjet interaction studies. The trade-off studies are executed in Task 8.1 during the synthesis stage in the course of mission and technical requirements analysis. Follow on tasks include CFD analysis of the hydrodynamic characteristics of the large HST, resistance, ship motions, seakeeping, and propulsion system evaluation. Utilizing CFD codes validated in the course of the CCDoTT FY00-02 studies, we developed hull forms and optimized the hull-waterjet and hull-propeller arrangement for the large HST. Large HST propulsion designs include innovative propeller and WJ designs and an improved performance estimate. This is accomplished by resistance prediction, hull forms optimization, and hull-waterjet interaction analysis. In Task 8.2 proven CFD MQLT tools to estimate speed-resistance and scaling factors for Trimaran ship specific hull forms are used. The hull-propulsion analysis builds upon the previous ONR/DASH project in 2001 and the model test results. This task is aimed at development of the analytical methodology to enable analysis of the innovative Trimaran hull forms, which utilize favorable hull-waterjet interaction phenomenon.

1. HALSS HULL FORMS DEVELOPMENT & TRADEOFFS

HALSS hull forms very generated based on technical requirements of the Task 8.1 and previous experience of hull forms optimization for VHSST-50, VHSST-330 and VHSST-200. The overall initial sizing of the HALSS is the following:

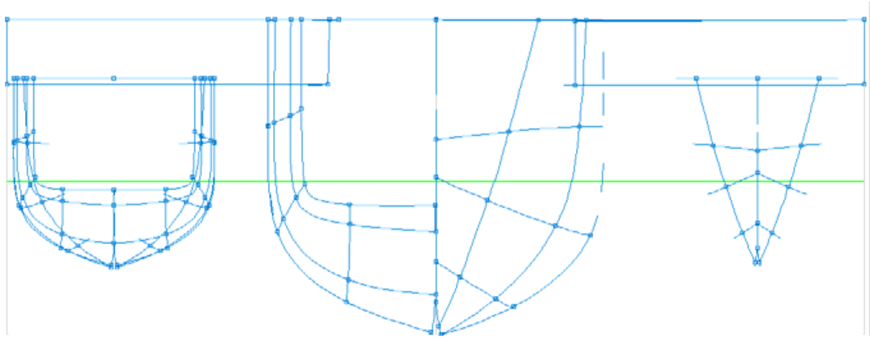
Principal Dimensions			
	Center Hull	**Side Hull**	**VHSST-2000 Total**
Length	330 m	200 m	330 m
Beam WL/Maximum	26 m	4.5/7.5 m	54 m
Draft maximum	11.5 m	11.5 m	11.5 m
Displacement	46,000 mt	7,000 mt	60,000 mt
Block Coefficient	0.47	0.52	n/a
LCB (from transoms)	142 m	90 m	138 m

1.1 HALSS Waterjet Propulsion Configuration with SWA type of the side hulls

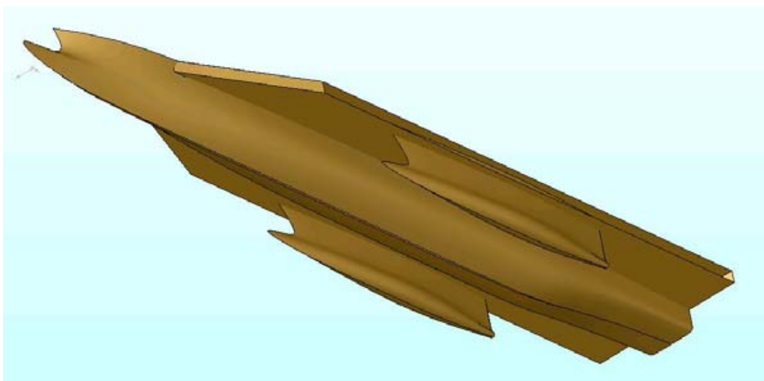
In the course of the hull parametric analysis the following variants were studied:

1. SWATH-type of the side hull forms. The MQLT calculations showed resistance advantages in comparison with conventional slender side hulls as developed in the previous CCDOTT projects for VHSST-50 and VHSST-200. Besides the following considerations were taken into account:
    - In case of Side hull waterjet propulsion option the multi-speed requirement for the HALSS indicates that waterjet propulsion in the side hulls being operated at low speed would request large waterjet unit, which would run at low efficiency in comparison with water jets, running at high speed. If this waterjet propulsion system arrangement is fully submerged, then the physical phenomenon of hull waterjet interactions takes place. As shown in previous studies, this phenomenon is favorable in terms of increasing the thrust or ship resistance reduction. The experimental proof of that was provided in model testing of the so-called Small Waterplane Area Trimaran (SWAT) hull forms. In case of VHSST-200 and HALSS only side hulls are SWAT-type, thus reducing the overall favorable effect of the hull-waterjet interaction, but having it probably enough to compensate the drop of efficiency of the side hull waterjet propulsion units operating at low speeds. This issue has to be investigated at further design stages using theoretical and model testing studies.
    - Another issue, which led to the SWA-type of the side hulls, is to eliminate air injection in the waterjet inlets at ship rolling in rough seas.
    - SWA side hulls allows increase (in comparison with conventional hulls) the clearance between the hulls – critical hydrodynamic factor for this type of the configuration.

2. Initially the configuration of the side hulls was chosen with different side hulls, as shown in figures below.

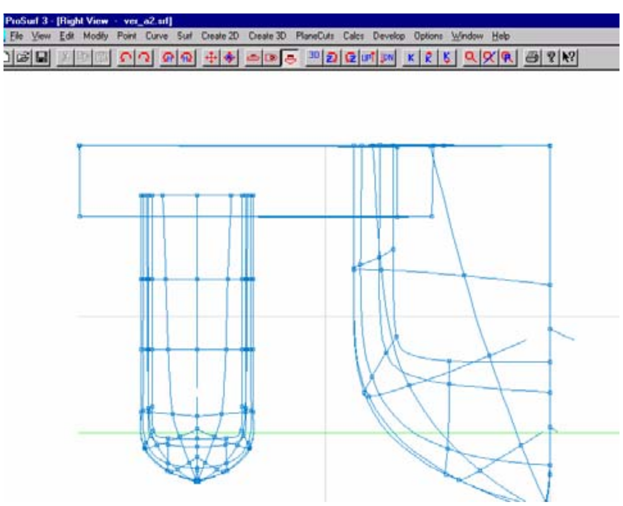


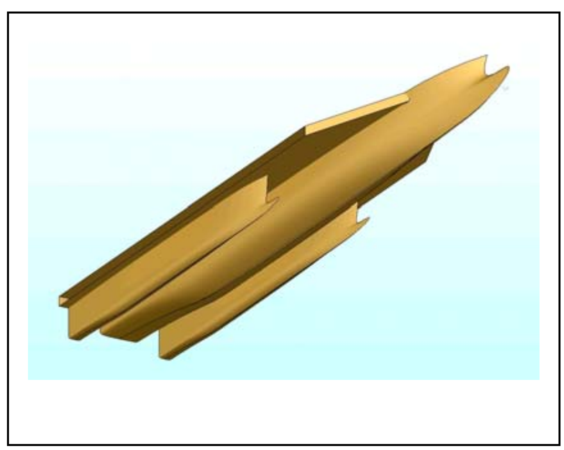
Another variant with SWA side hulls was generated as show in the following figure:



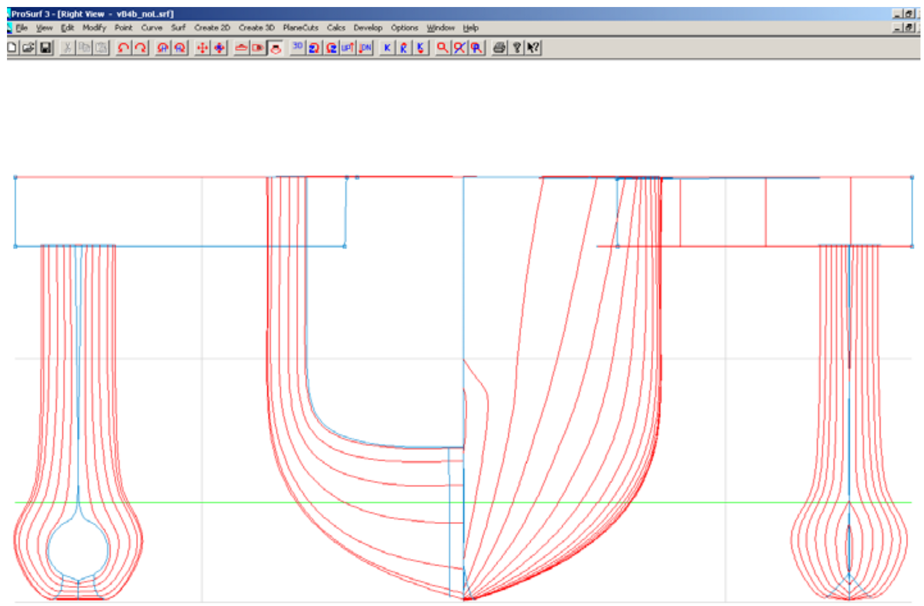
Length of side hulls had the same proportion to center hull as in VHSST-200
Drafts of side and center hulls are equal. However, hydrodynamic characteristics and design consideration first of all structural support of the main flight deck and required machinery arrangement in the side hulls were not satisfactory.

One of the initial variants of the HALSS hull forms with extended-draft, conventional side hull:

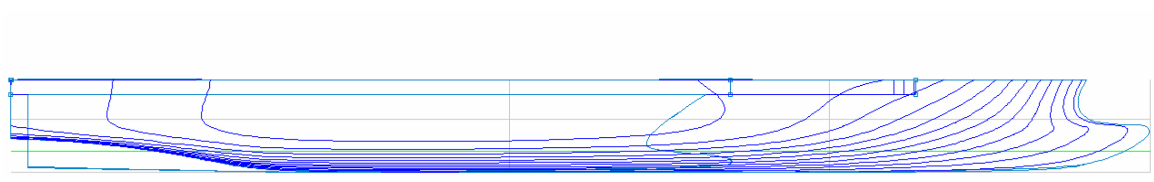




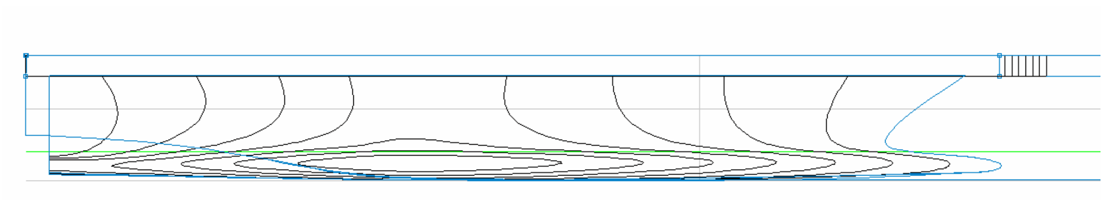
As results of analysis of these variants the HALSS hull forms were generated as shown in the Figure 1.



Left / right flip position = 216m from bow (amidships of side hull)
22 section lines @ 15m spacing



Center-hull profiles
12 section lines @ 1m spacing (0.5 to 11.5m from CL)



Side-hull profiles (close-up)
7 section lines (black) @ 0.5m spacing (0.5 to 3.5m from side-hull CL)

FIGURE 1. HALSS BASELINE HULL FORMS

1.2 Tradeoffs and Center Hull Forms Development for Propeller Propulsion

Basic tradeoffs included waterjet and propeller propulsion options. There are pros and cons for each type of propulsion. This analysis is partially described in Task 8.1 report and in more details – in Task 8.3 report, which is specially devoted to the propulsion design issues. From the point of hull development these options indicate different hull forms, especially in the center hull. The propelled center hull stern has to be redesigned with special skegs, which are necessary from the point of shaft arrangement, adding necessary space for huge machinery foundations, optimization of wake characteristics. Hydro dynamically skegged stern has to be designed with resistance and wake criterions in mind and constrains related to machinery arrangement. Optimized skeg geometrical variables are the sizes and two angles: vertical (in section view) and horizontal (in plane view). The refined selection of these variables would be provided in FY05 project. Here the task was to define the initial feasible variant of the skegged stern.

Below the sketch of machinery arrangement is shown. This information had indicated the constrains for the skegged stern geometry definition.

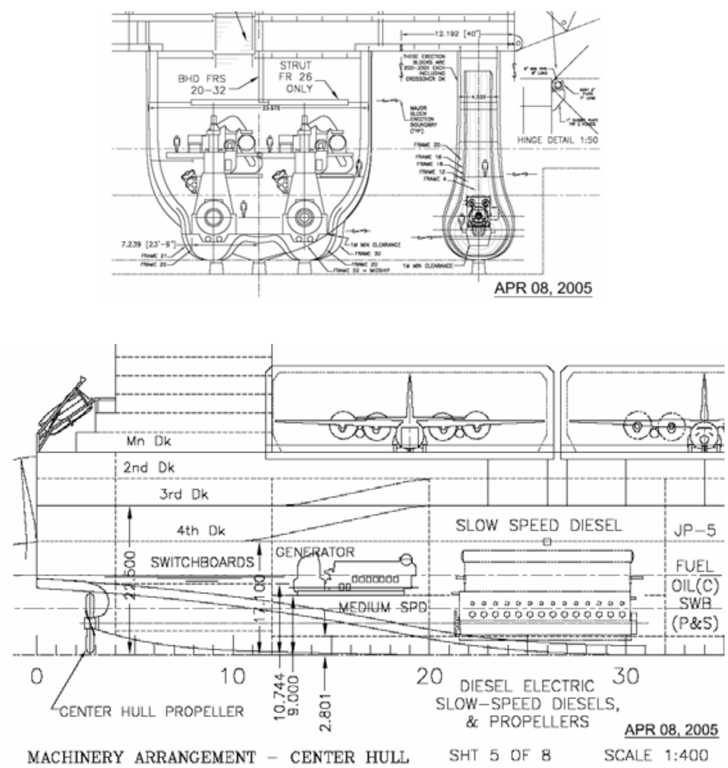
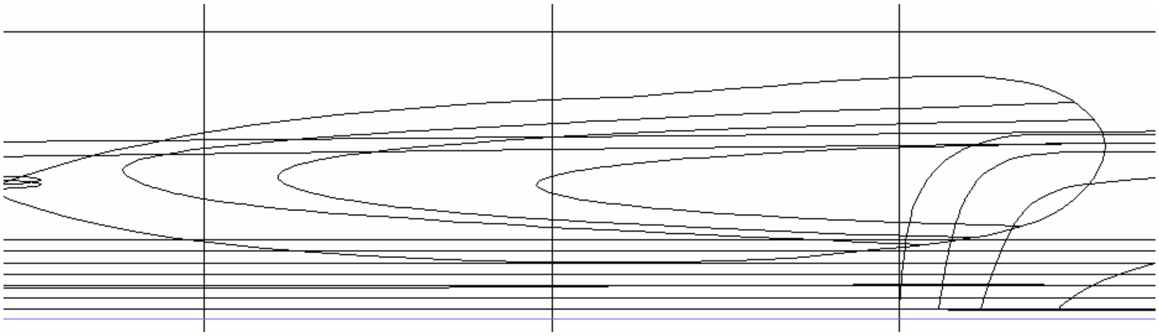


FIGURE 2. MACHINERY ARRANGEMENT FOR HALSS PROPELLER PROPULSION VERSION

The results of the generation of the hull forms are shown in Figure 3.



LINES OF THE STERN SKEG

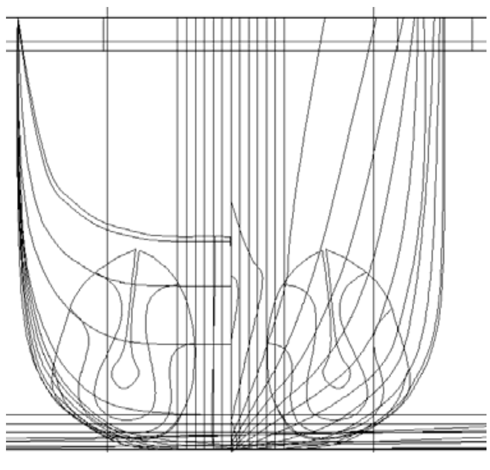


FIGURE 3. HULL LINES FOR THE HALSS PROPELLER OPTION

Basic design requirement such as stability, construction, general and machinery arrangement produce a set of general design constrains, which does not allow development of the hull forms with minimal achievable resistance. An example is the shape of the center hull and side hulls stern, which are constrained by propulsion arrangement; necessary displacement and volumes to install all needed machinery propulsion in the center and in the side hulls, especially for the propeller propulsion option; maximum length and overall beam, which is constrained by the construction facilities and so on. Moving further according the design spiral some of the basic assumptions and previous solution might change, thus opening opportunities to introduce necessary changes that improve the overall design. The goal of the preliminary analysis is to identify the areas where the additional research is needed and directions to improve the quality of the design.

HALSS side hull configuration analysis showed the following:

1) The side hulls are moved slightly forward about 30 meters. This solution leads to about 5% reduction of the coefficient of the wave resistance. Meanwhile the interference between the side hull propulsion and the center hull has to be investigated more carefully than in case where the propulsors are at the same longitudinal position. It is also expected that it would improve maneuverability, which would be studied at further design stages. Also, other design considerations

like ballasting and structural loading should be taken into account for final decision about the side hull configurations.

2) With overall beam constraints any changes in the transverse position of the side hull rather than maximum width are not favorable for HALSS sizes and speed.

HALSS center hull forms development requires further work in the following areas:

3) Fairing of the hull forms especially for the skegged stern of the propeller propulsion option. Simultaneously with fairing, the hydrodynamic optimization is necessary for the skegs and transom of this variant. This optimization has to take into consideration resistance and wake, and should be provided with use of CFD calculations and experimental results. One of the means would be the usage of experimental streamline for defining skeg angles in order to improve wake characteristics.
4) Structural aspects and motion predictions should be also taken into consideration while fairing the bow part of the hull.

2. RESISTANCE ANALYSIS AND FULL RANGE POWERING PREDICTIONS

2.1 Resistance Calculation Methodology

HALSS hull forms analysis and design recommendations were provided with the usage of the MQLT methodology, described in the previous CCDOTT reports and in the intermediate Task 8.1 report. Here we would remind that the MQLT is a numerical technique for high-speed trimaran resistance calculations. The technique is based on the modified viscous-inviscid interaction concept and quasi-linear theory of wave resistance. The key element of the technique, which is called Modified Quasi-Linear Theory (MQLT) method, is an account of Froude number influence on the ship trim, transom drag and wetted surface. This influence leads to appearance of a drag component that significantly depends on both Reynolds number and Froude number.

The Modified QLT (MQLT) calculations of residuary drag of trimaran take into account the following drag's components:

- Wave resistance at its dynamic trim and sinkage;
- Form resistance (including the transom's contribution);
- Friction's variation due to the dynamic variations of the wetted surface.

Here we would provide the application of MQLT for the Viscous-Inviscid Resistance calculations of the HALSS preliminary hull forms.

2.2 Analysis of the Viscous-Inviscid Resistance Calculations

We would define the coefficient of the total resistance as the following:

CT(Fn, Re) = CW(Fn) + CFOR(Fn, Re) + CF0(Re) (1)

Here Fn – Froude number;
Re – Reynolds number;
CT – Coefficient of the total resistance;
CW – Coefficient of the wave resistance;
CFOR – Coefficient of the viscous-inviscid form resistance, which takes account of transom, and form viscous-inviscid parts of the resistance and part of the friction drag due to the change of the dynamic wetted surface. All components of the CFOR are dependent from Fn and Re.
CF0 – ITTC friction drag

Correspondingly, we would define ;
CR(Fn, Re) = CW + CFOR, where CR – Coefficient of the residual resistance.
In model scale formula (1) looks as the following:
CTm = CWm + CFORm + CF0m = CRm + CF0m (2)
In ship scale:
CTs = CWs + CFORs + CF0s + CA (3)

where CA – correlation allowance coefficient, which is taken according David Taylor Model Basin recommendation to be "0" in HALSS power prediction (Crook, 2000).

To calculate (3) we would use conventional and new considerations based on MQLT methodology and calculation results. Conventional approach is that CWm = CWs. Based on MQLT we take into account the viscous-inviscid interference drag components and their relationship on Re, thus we cannot assume that CFORm = CFORs. The corresponding difference is defined in previous reports as the Scale Correlation Coefficient – SCC. Being estimated from the MQLT calculations and comparison of CRm and CRs this coefficient can be introduced to the formula (3):

$$CTs = CRm + SCC + CA \quad (4)$$

$$\text{Where } SCC = CRs - CRm = CFORs - CFORm \quad (5)$$

The calculations of the HALSS hull forms are shown in the Figure 4.

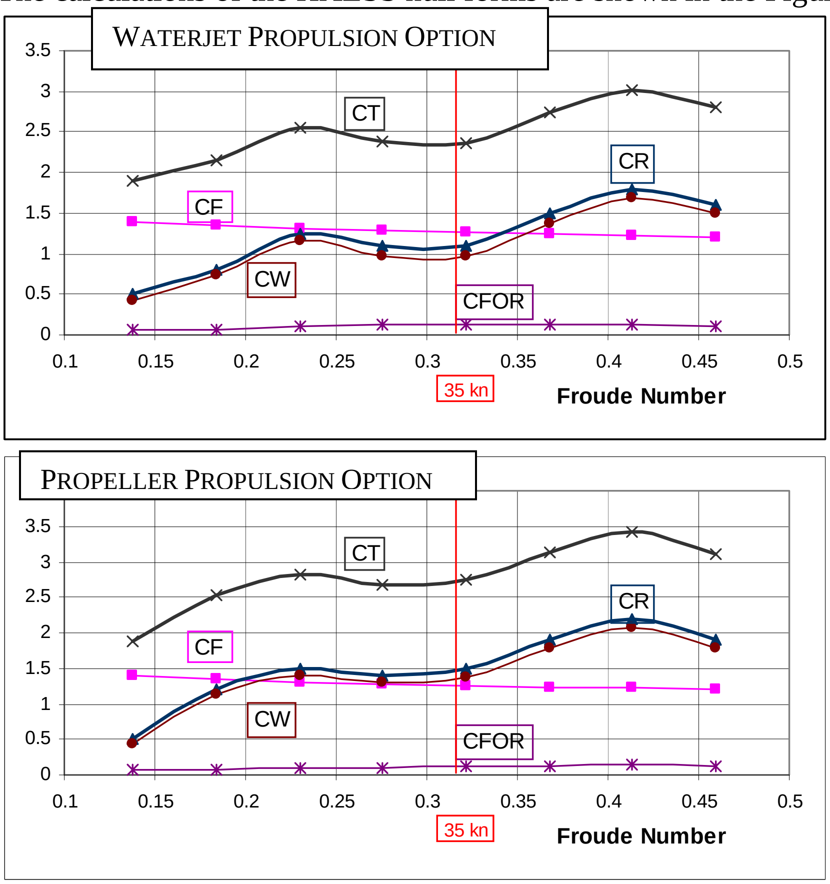


FIGURE 4. RESULTS OF THE CALCULATIONS FOR THE BOTH BASELINE HALSS HULL FORMS. HERE CF IS THE COEFFICIENT OF ITTC FRICTION RESISTANCE. CT IS THE COEFFICIENT OF TOTAL RESISTANCE AS DEFINED IN (1). CW – COEFFICIENT OF THE WAVE RESISTANCE, WHICH IS CALCULATED ON THE BASE OF THE QLT METHOD. CR – COEFFICIENT OF THE RESIDUAL RESISTANCE AS THE SUM OF CW AND CFOR. CFOR – COEFFICIENT OF VISCOUS-INVISCID RESISTANCE CALCULATED BY MQLT, WHICH TAKES AN ACCOUNT A CHANGE OF FRICTION PART OF THE RESISTANCE DUE TO THE DYNAMIC RUNNING TRIM AND WETTED SURFACE, TRANSOM AND FORM DRAG.

The conclusions after analysis of these calculation results can be made as following:

1. The wave resistance of the HALSS hull forms at trial Froude number, which is about 0.32 is better than for the VHSST-50. That is explained by increase of the

length to beam ratio of center hull (the length to beam ratio is 14 instead of 12 for VHSST-50) reduced beam to draught ratio for the side hulls. Accordingly, if the concept of the machinery arrangement would not be changed, the initial hull forms can be approved for the further design stages.

2. Viscous-inviscid resistance, which is measured by CFOR for VHSST-50 is at the same level as for HALSS. As a balance the total non-dimensional resistance of the HALSS is better than VHSST-50.

2.3 HALSS Speed-Power prediction

The summary of effective power is shown in the Figure 5.

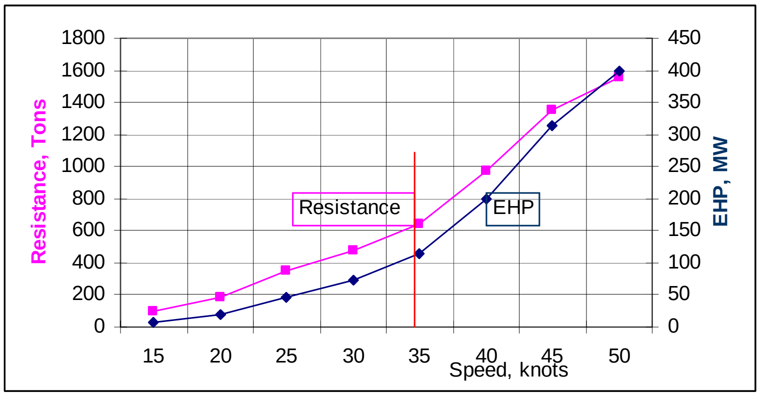
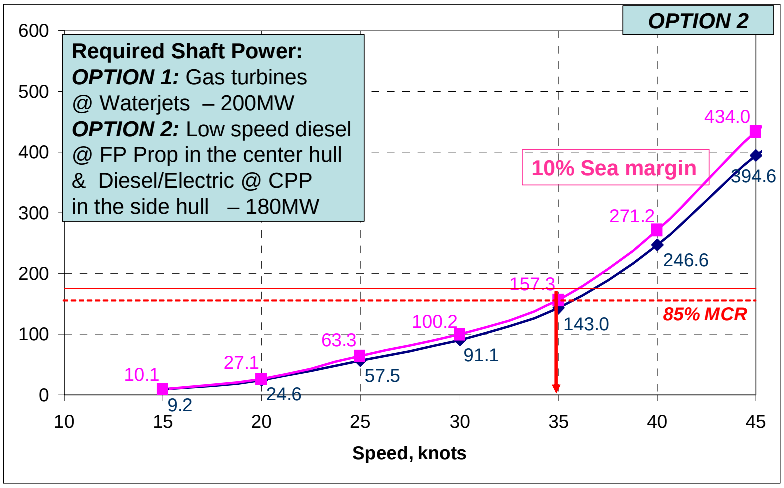


FIGURE 5. EHP PREDICTION FOR THE HALSS.

On the base of the comprehensive calculation results and comparison with testing data the correction of the power prediction based on scale factor has to be provided in further study. The correction based on the account of the hull-propulsion interaction factor can be further proved by R&D and experimental study.

The HALSS speed estimate is shown in the Figure 4. This estimate is provided at 85%MCR, and at 10% sea power margin. The results show that at this power level the trial speed is 35 knots, if no corrections are made. With reasonable correction with account of scaling factor the achievable trial speed is 37 knots. If we would take into account the hull-propulsion interaction factor the speed can be estimated to be 38 knots. These speeds are determined in the assumption of probably excessive 10% sea power margin. Having in mind exceptional good sea keeping quality of the slender trimaran hull forms, proved in the set of seakeeing tests in head seas at Sea State 5, 7 and 8 for the VHSST-50 and DASH “Slender” and SWAT large trimaran ships, where at Sea State 5 the resistance increase was less than 5%, we would recommend to use 10% power sea margin. In this case the estimated speed prediction at 90%MCR would increase for at least one knot and correspondingly the speed with all power prediction corrections would achieve 36 knots and the speed with only scale correlation factor would be 37-38 knots.

HALSS Speed Versus Power Diagram



3. HULL-WATERJET INTERACTION AND POWER PREDICTION CORRELATION FACTOR FOR WATERJET PROPULSION OPTION

With the waterjet's increase in size, especially in case of the HALSS with 40 MW waterjet, technical and financial risks increase as well. These factors heighten the need for a better understanding of how the hull affects each other's performance and what the interactions are.

Since the hull will be propelled by a waterjet, the flow around the aft body and in the wake area behind the transom will be considerably different than that experienced by the towed model in the basin. The separation zone will be then replaced downstream of transom by a jet outflow from the nozzle of the waterjet. This changed flow pattern implies lower resistive force on the hull when propelled (a reduction in the form drag associated with separated flow at the transom).

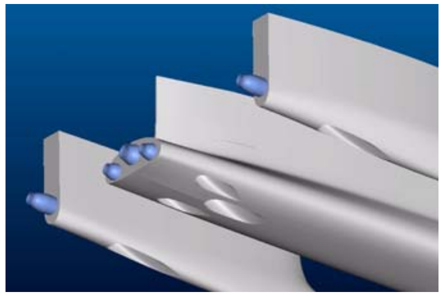
In particular, there is the need for more precise thrust and resistance predictions. A problem exists for the Naval Architect in knowing how a vessel will behave with the propulsion fitted (K.Alexander and T. van Terwisga, 1994). The difference between bare-hull resistance and self-propelled thrust is currently accounted for by a factor known as the trust deduction factor, which can be defined in the following way:

$$t_{CORR} = \frac{(T_s - R_{bhs})}{T_s} \qquad (6)$$

The correlation factor t_{corr} has the form of a thrust deduction (6), where R_{bhs} is the predicted bare hull resistance from model tests and T_s is the full-scale derived thrust. In some cases interaction is said to lead to a reduction in hull resistance, in others an increase. Propulsion testing provided by van Terwisga, 1991, Bjarne, 1990 and Swenson et al., 1998 has indicated a trust deduction characteristics ranging from +20% to –10%. A significant negative trust deduction if it takes place for the high-speed ship is of great interest to designers as well as to waterjet manufactures as it means that the waterjet-hull combination reduces ship resistance, enhancing ship performance at high speeds with the waterjet propulsion systems.

Reliable performance prediction for waterjet-propelled crafts requires self-propulsion tests. As it was stated in 21st ITTC and RINA's 2001 Waterjet Propulsion Conference Recommendations, "resistance tests only may lead to serious errors". From another point, a propulsion system design starts with the resistance curve of the bare hull.

In the course of the 2000-2001 ONR funded DASH Project, the slender trimaran hull concept with speeds up to 70 knots was studied and tested in David Taylor Model Basin and this problem had come under consideration especially for the hull forms of the so called Small Waterplane Area Trimaran (SWAT). This hull has a wide submerged transom, designed for three super-powered waterjets. An attempt was provided to find the theoretical approach to simulate hull-waterjet interaction effect by distribution of sources at the location of waterjet outlets, momentum flux method and special inverse hydrodynamic problems solver. Figure below shows the view of the SWAT transom stern tested to identify the hull-waterjet interaction phenomena.



HULL-WATERJET ARRANGEMENT OF THE SMALL WATERPLANE AREA TRIMARAN SHIP.

The results of preliminary estimates led to the Concept of "Waterjet-Simulating Imitator" (WSI) additional specially shaped bodies to be attached to the submerged part of the transom to simulate in resistance tests (and calculations) variation of the after-stern water flow and induced forces & moments induced by the running waterjet system. The model test results showed substantial reduction of the total resistance of the models with "Imitators" in comparison with bare hull model tests, thus indicating that in the case of the SWAT hull forms the correlation factor (6) can reach a value of almost –30% at speed range 50-70 knots. The results of the model tests are shown in the Figure 6. This Figure represents the resistance in pounds, measured in the full range of ship speeds. It can be seen that nevertheless the wetted surface increase from about 15% - 25% for different types of WSI (PEI, TPI and TEI at Figure 4 are the types of WSI) the measured resistance dropped to 10%-15% from the resistance of the bare hull.

FIGURE 6. MEASURED TOTAL RESISTANCE OF TOWED SHIP MODELS WITH THREE TYPES OF WATERJET SIMULATING IMITATORS (WSI).

Figure 5 shows the change in Coefficient of the residual resistance vs different types of WSI's. The change in CR demonstrates the experimental basis to introduce the correlation factor, which allows us to take into account the hull-waterjet interaction phenomena and to correct the total resistance prediction.

The mentioned experimental results clearly show a high possible WSI's effect on the total ship resistance. The coupled problem is to find a theoretical method to design WSI for the given pairs hull/waterjet and validate such a method by experiments with both self-propellant and towed ship models.

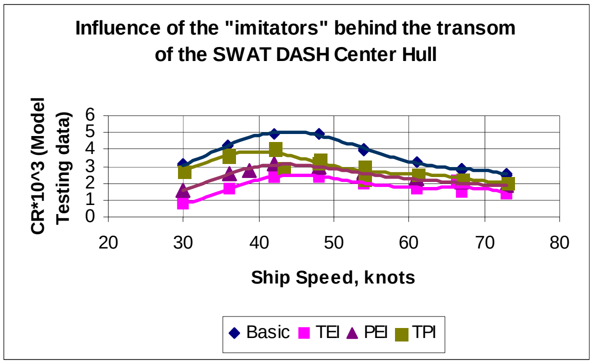


FIGURE 7. HULL-WATERJET INTERACTION SIMULATION RESULTS.

As a result of this analysis the coefficient "t_{cor}" (6) can be estimated to be 15-25% and in terms of general resistance prediction formula (5) the Coefficient Ct can be presented in the following way:

$$CTs = CRm + CF0s + SCC + CA + HWCC \qquad (7)$$

Where Hull-Waterjet Correlation Coefficient (HWCC) substitutes correlation coefficient (6) and conservatively, based of the tests provided for the SWAT trim ran hull forms, can be estimated to be –0.0005.

It is traditional to forestall tests of self-propelled ship models by towing tank tests of their bare hulls. An optimization of hull's shape is usually validated in experiments with towed models. However, a very significant effect of hull-propulsor interaction on pressure distribution over hulls is inherent for fast ships with wetted transoms and makes it difficult to follow the traditional path. There is certainly boundary layer separation for towed models (as it was shown in towing tests of high-speed slender hulls with hull slenderness 10, where relatively high values of CR at low speeds were clearly associated with viscous separation). For full-scale conditions, this separation can be suppressed (or even removed) by the inverse influence of propulsor jet. As a result, the residuary drag coefficient CR cannot be directly extrapolated from towed models to a full-scale ship propelled by waterjet. This problem needs clarification for further HALSS design.

The necessary extrapolation cannot be completely based on testing self-propelled models because there are significant scale effects for both waterjet and the ship's boundary layer (ITTC-21, 1996). Particularly, the ratio of the velocity in the jet, V_J, to the ship speed, V_S, is always higher for models because their friction coefficients are much higher (Alison, 1992). The self-propelled model test results unavoidably require sophisticated extrapolations to be applicable to full-scale conditions. This situation urges us to look for possible improving of towing tests. It is desirable to deflect the streamlines behind the stern of towed model closer to streamlines of a full-scale self-propelled ship (as closed as possible). A streamline deflection could be caused by a WSI jointed to the stern. Generally, the coincidence of streamlines requires the coincidence of pressure distribution. The boundary layer growth will be expected to be similar, etc. The coincidence of pressure distributions would guaranty both the same form resistance and the same friction drag (for a fixed Rn).

Evaluation of the tools to model the significant effect of hull-waterjet interactions on pressure/velocity distribution over the hull and wake flow is the general goal of further study. This study consists of the theoretical and experimental work needed to provide an understanding of the causes and mechanisms of hull-waterjet interactions and the use of CFD computation and model test results to gain the ability to predict interaction forces and correlation factors from the model resistance data for estimating the full scale resistance and thrust of high-speed ships with waterjet propulsion systems.

Theoretical explanation and objectives of the proposed further work to prove power prediction methodology with hull-waterjet interaction factors are presented in the next paragraph.

3A. THEORETICAL BACKGROUND AND OBJECTIVE OF THE HULL-WATERJET INTERACTION STUDY AND CORRELATION FACTOR PREDICTION

First of all, it is necessary to perform self-propelled test with a specially designed model and waterjets. Why is it necessary to perform the special design? Of course, there is a lot of tested self-propelled models of waterjet ships, but their waterjet design was aimed to achieve a maximum efficiency at one jet velocity ratio. This limits the usage of the experimental data for comparison with numerical results in the full range of ship speeds and jet velocity factors.

A specially designed model makes it possible to perform multiple validations because the waterjets can be designed without regards to their efficiency. A specially designed multi-propulsor ship model is the most suitable for the research objectives. A rimaran with three water jets is an especially attractive model because of the possibility of different combinations of thrust of the three running/not running water jets at the same speed.

Objective 1: Develop a method to design imitators for the hull-jet configuration.

Determine a body shape by using a desirable pressure distribution over its surface is an Inverse Hydrodynamic Problem. It is not a completely novel inverse problem to design WSI. A similar problem was considered for model tests of water inlet pods, and an illustration of its solution (Amromin et all, 1996) is shown in Figure A-1. There is a practical coincidence in the pressure distributions for the pod with the wide-open inlet and for the impermeable imitator, but the imitator slenderness is much higher (by the factor 1.5). Such changes of shape would be excessive for a ship's hull (a relevance of the model to the full-scale ship could then become questionable).

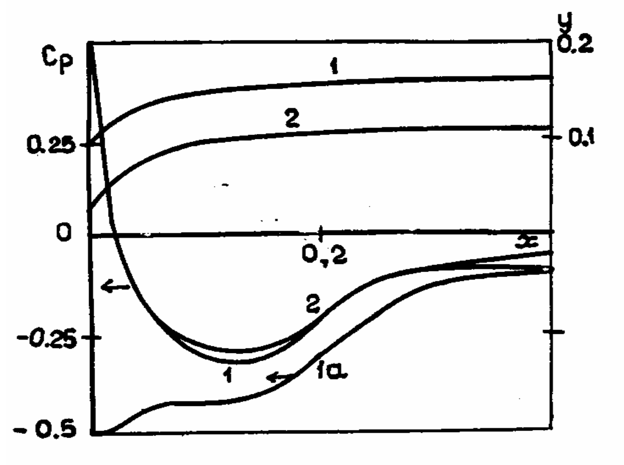


FIGURE A-1: COMPARISON OF FORMS AND PRESSURE DISTRIBUTIONS FOR WATER INLET POD NACA-1-60-125 FOR V_J/V_S =0.8 AND ITS IMITATOR (V_J/V_S =0). THE POD MERIDIAN SECTION AND THE RELEVANT DIMENSIONLESS PRESSURE COEFFICIENT C_P ARE PLOTTED BY THE CURVES 1, THE IMITATOR SECTION AND C_P ARE PLOTTED BY CURVES 2. ADDITIONALLY, CURVE 1A SHOWS C_P OVER THE POD WITH CLOSED INLET.

Determination of the WSI shape for a given hull and waterjet can be based on the distribution of sources over the hull and at the location of marine propeller or waterjet outlet. The total intensity Q_Σ of the sources depends on the propulsor thrust. Operating with dimensionless quantities, one has:

$$Q_\Sigma = \frac{Ts}{2S_J \rho V_S V_A} \tag{A.1}$$

Here S_J is the area of jet cross-section, Ts is the thrust, V_A is the incoming flow speed at the propulsor location (in the coordinate system clamped to ship). These sources interact with sources of intensity Q distributed over the rest of the hull's wetted surface part S. Because of this interaction, the Q distribution over S must satisfy the following boundary condition of potential theory:

$$\frac{1}{2\pi}\iint_S Q \frac{\partial}{\partial N}\frac{1}{R} ds - Q = 2N_X - \frac{1}{2\pi}\iint_{S_J} Q_\Sigma \frac{\partial}{\partial N}\frac{1}{R} ds \tag{A.2}$$

Here $R=[(x-\xi)^2+(y-\eta)^2+(z-\zeta)^2]^{1/2}$; {x,y,z} are coordinates of a point over S; {ξ,η,ζ} are coordinates of both surfaces; N is the normal vector to them. Designing an imitator, one has to replace S_J by another surface S_I while keeping the velocity perturbation in any point of S:

$$\iint_{S_I} Q(s) \frac{\partial}{\partial N}\frac{1}{R} ds = \iint_{S_J} Q_\Sigma(s) \frac{\partial}{\partial N}\frac{1}{R} ds \tag{A.3}$$

Although the right-hand side of Eq.(A.3) is a function of {x,y,z} that can be easily computed at any point of S, this integral Fredholm equation of the first kind has no smooth sole solution. Such an inverse problem is incorrect because a condition over the surface S must be with sources distributed over another surface. This inaccuracy means the existence of many oscillating exact solutions (very wavy designed surfaces), whereas a smooth approximate solution would be preferable.

There is also no single approximate solution, and a selection of the suitable approximate solution must be made with taking into account reasonable engineering restrictions. Therefore, it is necessary to develop a special method to find such an approximate solution and design the WSI with the same hull shape.

In the course of the previous DASH project the selection of WSIs was performed on the basis of a qualitative hydrodynamic analysis. The objective of that work was to obtain the design of the WSI by solving the inverse hydrodynamic problem for the same model that is employed in the self-propelled tests and run towing tests of this model with the designed WSIs. These WSIs were built as removable solid bodies, which were attached to the fully submerged transom of the bare hull. The tests with each WSIs obtained all the standard measurements for the resistance parameters. The results of tests are shown at Figure 4 and 5.

The suggested concept for the WSI evidently requires experimental validations. The hull-waterjet interaction phenomena can be interpreted (in case of negative correlation factor) as the propulsion having more thrust than normally expected, or the bare hull resistance is substantially reduced by the presence of the jets.

Objective 2: Determine boundary layer influence on pressure distribution in the vicinity of transom stern and introduce correlation allowance for full-scale conditions

There is an increase of boundary layer thickness around the side surfaces of any ship. There is also a sharp change of wake characteristics behind the transom sterns. It relates to both towed models and self-propelled ships. The waterjet outlets do not coincide with the transom edges, and separation of the boundary layers takes place there. There are two important effects of this separation: An additional drag and displacement of the streamlines (boundaries of inviscid flow). The running waterjet reduces this separation effect; nevertheless, it exists and must be taken into account.

It is important to emphasize that scale effects are caused mainly by the boundary layer influence. There is a direct scale effect on the viscous drag (for a fixed trim), but there are also experimental (Amstrong, 1999) and theoretical (Mizine et al, 2002) evidences that trim of fast multi-hulls undergoes a high scale effect and implicitly affects drag. A theoretical analysis can clarify the scale effect, but viscous separation behind the transom is difficult to handle theoretically. In spite of the successes in modeling of turbulent flows with RANS codes, numerical analysis of viscous separation has been a difficult problem. For example, the widely developed K-ε model is still unable to satisfactorily describe turbulent separation. There is a recent example (Iaccarino, 2001) of attempts to compute viscous separation past a cone (similar to sharp stern) with the commercial CFD codes Fluent v5.3 (developed by Fluent), CFX v4.3 (developed by

AEA Technologies), and Star-CD v3.1 (developed by Computational Dynamics Ltd). These codes predicted no reverse flow, although experiments show a significaunt reverse jet with velocities of 20% of free-stream speed.

Nevertheless, a recent success in computation of 2D turbulent separation was obtained with the viscous-inviscid interaction concept (Amromin et all, 2002). There are examples of successful computations of 2D flows with this concept in Figures A-2 and A-3.

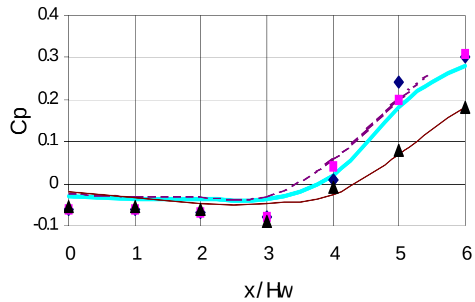


FIGURE A-2: COMPARISON OF CALCULATED (AMROMIN ET ALL, 2002) AND MEASURED (TANI ET ALL, 1961) COEFFICIENT CP PAST A BACKWARD FACING STEP IN A WIND TUNNEL. TRIANGLES ARE MEASURED DATA FOR FREE-STREAM SPEED U_∞=28M/S AND THE STEP HEIGHT HW=0.02M; THIN SOLID LINE IS CP COMPUTED FOR THIS PAIR. SQUARES ARE MEASURED DATA FOR U_∞=10M/S, HW=0.06M; THICK SOLID LINE IS COMPUTATION FOR THIS PAIR. RHOMBUS ARE MEASURED DATA FOR U_∞=28M/S, HW=0.06M; DASHED LINE IS COMPUTATION FOR THIS PAIR.

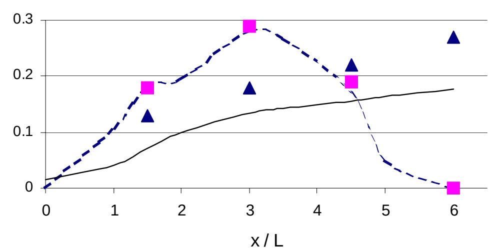


FIGURE A-4: COMPARISON OF MEASUREMENTS (TANI, ET ALL, 1961) AND CALCULATED (AMROMIN ET ALL, 2002) NORMALIZED VELOCITY PULSATION $[<u'u'>/U^2]^{1/2}$ AND THE MAXIMUM REVERSE VELOCITY U_M PAST THE BACKWARD STEP IN A WIND TUNNEL FOR U_∞=28M/S, HW=0.02M. THE MEASURED U_M AND $[<u'u'>/U^2]^{1/2}$ VALUES ARE PLOTTED BY SQUARES AND TRIANGLES, THE COMPUTED DATA – BY THE DASHED AND SOLID LINES.

A successful extrapolation of model test results to full-scale condition (as well as a successful imitator design) requires determine a 3D boundary layer effect on pressure distribution in the vicinity of transom stern, with taking into account existence of both separation zone and propulsor jets there. The difference in this effect for model and full-scale conditions must be used in prediction of correlation factor.

4. Lessons learned and further R&D and HALSS hull form development tasks.

Hull Forms development was based on previous studies:

- VHSST-50 hull forms development and model tests experience;
- DASH slender and SWAT hulls form development, calculation results, MQLT verification and analysis and DASH model tests results:
- Trimaran SSS trailership hull forms optimization results, in which SWA type of side hulls were developed and proved by comprehensive CFD analysis.

The HALSS hull forms are the result of choosing the balance of the following design criterions and requirements:

- High Speed Performance & Structural Requirements Compromise
- Excellent Seakeeping & Structural Support
- Enough Area/Volume for all of Propulsion Machinery Options

1. As a result of the trade-off studies, the side hulls were moved forward 30 meters. This change would be favorable from the point of resistance and from the structural point as well. The final decision should be made at further design stages, taking into consideration the present load conditions that require carriage of several hundred tons of ballast in the forepeak to achieve even keel draft with uniform cargo loads (including no load). This is obviously undesirable. A further tradeoff study should be done to evaluate the trim or ballast penalty against the benefit or penalty of moving the side hulls aft, to determine optimal location.
2. Another improvement was the SWA-type hull forms of the side hulls. It allowed reduced transom area and substantial improvement of running trim, dynamic wetted surface and viscous-inviscid resistance reduction. The problem here is the machinery and propulsion rearrangement. This is an existing alternative, which might lead to at least 5% of the power improvement of the hull forms in comparison with conventional side hull arrangement. For this variant the reduction of the resistance due to viscous-inviscid component would compensate and exceed the negative wetted surface increase. Prospective HALSS side hull forms, studied in the ONR/DASH project, would radically eliminate the transom drag, putting side hulls waterjet units below the waterline. In case of the SWAT type of the hull forms the correction based on hull-propulsion interaction factor becomes valid, because it was proved in the course of the model tests with SWAT type hull forms.
3. Results of the HALSS hull forms development analysis have shown a difference between model and ship scale residual resistance. This difference also depends on Fn, thus proving the 22^{nd} ITTC statement about form factor dependence on speed for high-speed vessels. That is why correct extrapolation of the model test results to full-scale condition is necessary for power prediction of the HALSS.
4. For advanced HALSS version, where the axial waterjet propulsion option is considered as the basic, results of CFD calculations and hull interaction analysis

showed that such interaction can provide a very favorable correlation, especially in case of SWA type of the hull. Further studies and experimentation are needed.

5. For propeller propulsion option hull forms of the center hull require further fairing with respect of resistance and wake characteristics. Such refinement has to be mostly provided for skeg stern design of the center hull.

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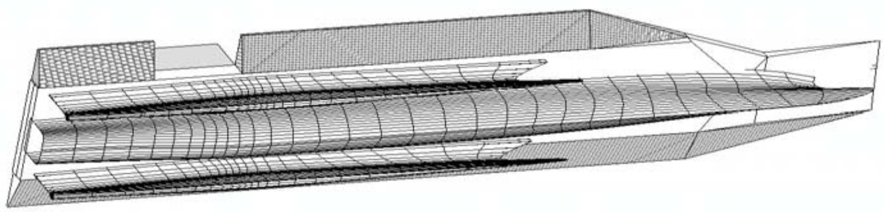
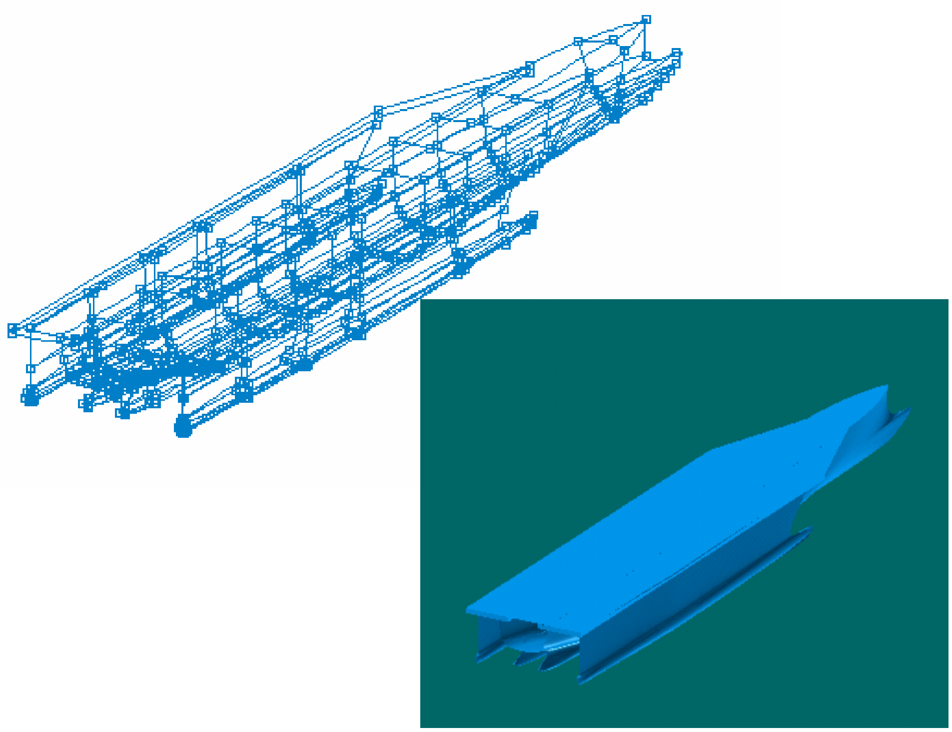
5. 3D VIEW OF HALSS HULL FORMS

HULL FORMS OF WATERJET PROPULSION HALSS OPTION



HULL FORMS OF PROPELLER PROPULSION HALSS OPTION



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