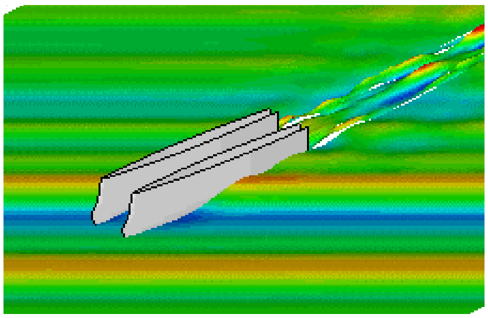
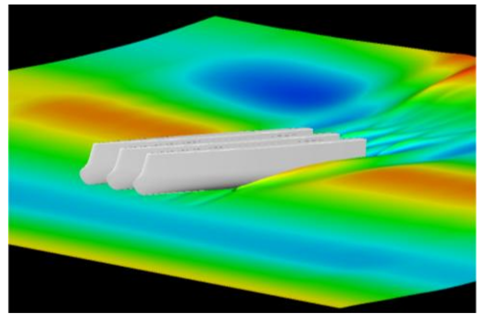
Computational Hydrodynamic Tools for High-Speed Sealift[1]

Fred Stern, Pablo Carrica, Mani Kandasamy[2]
Joe Gorski, John O'Dea, Mike Hughes, Ron Miller, Dane Hendrix[3]
David Kring[4], William Milewski[5]
Russ Hoffman, Charles Cary[6]





ABSTRACT

The determination of naval architectural parameters for high-speed ship design poses many challenges. CFD tools can assist ship designers in predicting the hydrodynamic performance of these often-unconventional hull forms, including resistance, powering and seakeeping. A team of naval architects, code developers, and hydrodynamists has assembled and evaluated a hydrodynamic design suite of computer codes that uses fast inviscid codes for the initial parametric studies and gross optimization, followed by URANS operating on high performance computing resources for detailed optimization and evaluation of ship performance. This paper describes the development, initial evaluation, and initial validation of this suite, applied to analysis of High Speed Sealift (HSSL) design concepts. The capability of the design suite to meet the naval architect's needs is demonstrated, at various stages of the design, and the codes are validated with available data.

[1] SMTC&E Final Draft (May 1)
[2] The University of Iowa, IIHR-Hydrosceince & Engineering
[3] Naval Surface Warfare Center, Carderock Division
[4] Flight Safety Technologies, Inc.
[5] Applied Physical Sciences Corp.
[6] Bath Iron Works/General Dynamics Company

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INTRODUCTION

Background

High-speed ships are of increasing interest for diverse applications including fast commuter services, fast ferries, fast cargo ships, and fast combatants requiring innovative hull designs and propulsion systems. The navy market for fast vessels stems from the need to respond quickly to distant trouble spots, requiring fuel efficiency and good seakeeping in high sea states. In addition, littoral operations require high speed in shallow water, beach landing, and amphibious capability as well. Semi-planing monohulls, catamarans, trimarans, supercavitating vessels, and foil supported lifting bodies with gas turbine water jets are some of the hull form and propulsion system concepts that are currently under consideration. Pacesetting hydrodynamics issues include reductions in breaking wave and especially viscous drag and structural loads, favorable seakeeping and maneuvering performance for high sea states, and shallow water performance, especially regarding far field waves and wash. Major factors affecting performance in high sea states are accelerations, added resistance due to waves, and structural loads. Added resistance will affect the ability to maintain the desired high speed, even in moderate seaways. Both slamming and main hull girder loads prediction is crucial for ship structural design. Classification society rules based on conventional ships do not apply for multi-hull configurations, requiring the use of more sophisticated computational methods. The other issue unique to multihull ships is the increased resistance due to hull interactions that depend on hull separation to length ratios (Molland et al., 1995). The recent FAST05 conference, 8th of its series, dedicated to fast sea transportation provided a representative forum for discussion of new concepts and designs of fast sealift ships and vehicles. Papers presented at this conference covered topics such as hydro-aerodynamics, structures and materials, maneuverability, propulsion, safety and operation, and infrastructure and economics of fast sea transportation (FAST05)

The current requirements for high-speed sealift (HSSL) that will allow rapid deployment of forces from CONUS to foreign ports are shown in Table 1. A significant issue is the length and draft restriction imposed by operation to austere ports, while maintaining the capability to carry the required payload at sustained high speed. To respond to these requirements, the Office of Naval Research (ONR) initiated a coordinated project consisting of various teams to further develop HSSL concepts and tools. Several teams are considering architectural concepts, while others are investigating computational tools. The work reported here are the initial results (phase I) of one of the teams investigating these tools. A later phase (phase II) will validate these tools and implement them in an expert system, with consistent input and output structure, for use in further HSSL ship design. This is a multi-disciplinary team consisting of approximately 17 hydrodynamicists and ship designers from the University of Iowa (UI), the industrial organizations Bath Iron Works (BIW), Flight Safety Technologies, Inc (FSTI), and Applied Physical Sciences Corp. (APS); and the Naval Surface Warfare Center, Carderock Division (NSWCCD).

The computational hydrodynamic tools being considered should be able to predict the resistance of multihull vessels up to at least sea state 4, propulsive performance, seakeeping and structural loads on these vessels through survival sea states, maneuvering characteristics of the vessels, and the effects of shallow water on the performance of the vessels. At present, there are no validated software packages capable of performing all of these computations for candidate HSSL vessels, but the team is investigating several codes, described below, that can address at least some of these requirements, at varying levels of fidelity.

Overall Objective

The overall objective of this effort is to provide the ability to predict the hydrodynamic performance of the non-traditional hull forms that are necessary to meet the HSSL mission requirements and to explore the parameter space of these designs. This will require a unified capability to perform a broad range of hydrodynamic computations and predictions at several levels of fidelity, necessitating a broad range of computational resources. To facilitate timely and efficient design efforts, these computational tools, their inputs, outputs, information on using them and common interfaces will be brought together in an "expert system" along with information on relevant available experimental data and hull form designs.

The effort includes two phases. in the first phase, described in this paper, the initial HSSL hull form and propulsor concepts were developed and the ship architect's needs identified. Optimization opportunities have also been identified. The various computational tools were assembled and evaluated, and initial validation carried out using data sets available for existing high-speed multihulls. The design suite demonstrates the ability to meet all of the naval architect's needs to investigate HSSL concept performance.

Future work in the second phase will include further code validation and improvement of the HSSL design suite. In addition, the group will demonstrate the design process for optimizing the hull form. The group will explore concept performance (both original and optimized concepts) for a subset parameter range of interest, based on full parameter ranges identified for the different disciplines such as resistance, sea-keeping, propulsion and maneuvering. Proving predictive capability for the selected subset range of parameters, and hence the whole parameter range, the group will finalize the hydrodynamic tools package after testing and feedback from users. Based on computed results, important data acquisition locations will be identified for experiment test design.

Approach

The ability to perform parametric studies as part of preliminary design, optimize hull forms, and perform detailed analysis of HSSL designs requires a multi-tiered approach to the selection and application of hydrodynamic tools. The parametric studies and gross optimization of the HSSL designs require relatively simple analysis tools, which run quickly on a personal computer or workstation. The detailed optimization of the hull form and sophisticated analysis of the resulting vessel's performance will require sophisticated hydrodynamic tools used by experienced hydrodynamicists using high performance computing (HPC) resources. All levels of the design will need common geometric representations that will allow preparation of input for the various computational tools with minimal user intervention at the vessel configuration level.

Accordingly, the first phase of HSSL hydrodynamic design occurs in three stages. Stage 1 entails assembly of HSSL concepts and the various software packages. Fig 1 provides the list of hydrodynamics tools and their capabilities. Stage 2 entails concept revision with two main undertakings namely a) early stage design and evaluation, and b) detailed analysis and evaluation.

The early stage design, at the parametric analysis level, requires simple tools that are capable of predicting resistance, motions, and operability, as well as optimization of the gross characteristics of the design. At this stage of design, slender ship theory provides resistance prediction capability for wave resistance, and simple skin friction and form factor methods or boundary layer methods predict viscous drag. The seakeeping aspects of the design can be characterized by the use of high-speed strip theory. The primary structural loads are also predicted using high-speed strip theory. The optimization of the gross hull form characteristics during this early stage of the design will be treated by parametric variation of the characteristics and further by refinement of the hull form within the slender-ship resistance prediction methodology. At this stage of the design, simple propulsor models that do not employ significant detail are used to estimate the design's propulsion characteristics. The component codes of the early stage design are TSD (Resistance characteristics), and VERES *(*Seakeeping and loads prediction).

Following early stage design, in the second stage the detailed analysis and evaluation uses boundary element methods (AEGIR), and URANS (CFDShip-Iowa) for the following: resistance characteristics of hull form, detailed flow field and maneuvering characteristics, prediction of unsteady loads in head seas (up to sea state 5), propulsor performance, and roll damping, seakeeping and load prediction. These investigations serve as a basis for detailed optimization. The cost functions for multihull drag minimization and multihull seakeeping optimization are defined. CFDShip interfaces with modified optimization modules for CFD-based hull form single/multiple and local/global optimization on HPC platforms based on the cost functions (collaboration with INSEAN, Italy and University of Osaka Prefecture, Japan). A team separate from the code developers evaluates the code performance. Fig 2 portrays the overall operational synergy between the code developers, code users (evaluation team), and naval architects.

CONCEPTUAL DESIGN

Hull Form and Propulsor Concepts

BIW provided four different concept geometries to the team, a catamaran and trimaran for design development (HSSL-A), and a catamaran and trimaran for optimization demonstration (HSSL-B). The catamarans possessed identical port and starboard hulls, and the trimarans had three equal hulls. One catamaran-trimaran pair was developed using the proven high speed DASH stabilized monohull as a parent hull form, and the other pair was similarly based on the Bathmax high-speed container ship. Both feature slender hulls, gas turbine and water jet propulsion, unobstructed weather decks suitable for flight operations, an innovative bow form to enable beaching, and the ability to extend a ramp onto the beach, and eventual withdrawal from the beach. Being proprietary, HSSL-A detailed geometry cannot be shown. However, Fig 3 and 4 show the HSSL-B catamaran and trimaran geometries, respectively, which are conceptually similar to HSSL-A. Fig 5 shows the blueprint of the proposed water jet based on UI and BIW power calculation.

Optimization

The parametric studies and gross optimization of the HSSL designs require relatively simple analysis tools, which run quickly on a personal computer or workstation. The detailed optimization of the hull form and sophisticated analysis of the resulting vessel's performance will require more sophisticated hydrodynamic tools and high performance computing (HPC) resources. All levels of the design will need common geometric representations that will allow preparation of input for the various computational tools with minimal user intervention at the vessel configuration level. Table 2 shows a sample of the hull form optimizations of interest. This table illustrates how the objective functions for optimization may include resistance at one or more speeds, and measures of seakeeping at several locations on the ship. The overall objective function can include weighted sums of these performance measures. The geometric constraints are intentionally broad, and will permit non-symmetrical individual hulls. Without such freedom, the multihulls experience significant cross flow and resulting drag.

Computational Requirements

Table 3 shows the naval architect's needs from the computational tools at different stages of the design cycle. As the HSSL concept proceeds through more detailed design stages, more detailed and more accurate hydrodynamic results will be required. For example, at the concept design stage, only calm water power might be estimated, together with simplified estimates of seakeeping, loads and maneuverability. As the design progresses, the more sophisticated hydrodynamic tools will be used to provide more complete performance evaluation.

For resistance and power both effective and delivered power are required as well as added resistance in waves. Motions and habitability typically involves rigid body 6DOF motions and the computation of Response Amplitude Operators (RAOs). From these computations of the hydrodynamics of the ship operating in waves comes the ability to provide load estimates. Beyond the computation of RAOs and loads is the very important aspect of evaluating operability of the ship. Such operability evaluations might entail determining limiting wave heights for various operational scenarios such as transits, underway replenishments, and aircraft operations. Finally, maneuverability needs to be assessed, both in terms of directional stability and also the ability to predict the maneuvering behavior of the ship.

COMPUTATIONAL HYDRODYNAMIC TOOLS

The following summarize the computational tools evaluated for use in the HSSL project. Several tools are for specific areas shown in Fig. 1, such as TSD for resistance and VERES for ship motions, while several others are multi-purpose. AEGIR can be used to estimate ship motions as well as calm water resistance, while CFDShip can be used to estimate resistance, propulsion, maneuvering and motions in waves.

TSD

TSD (total ship drag) is a robust fast resistance prediction tool appropriate for early stage design developed by NSWC/CD (Metcalf, et al. 2004). The total drag of a ship as calculated by TSD is made up of the following components: wave-making resistance, frictional resistance, form resistance, transom drag, and other drag. Each resistance component is estimated in a way that is faithful to the physics of the problem. The wave-making resistance is computed using Noblesse slender ship theory (Noblesse, 1983). The frictional resistance is estimated using the ITTC friction line. Form resistance is approximated from Series 58 data. Transom drag is divided into two components—a base drag component which is modeled based on empirical data from sub-sonic bullet tests, and a hydrostatic component which accounts for the missing hydrostatic pressure on a dry transom. Finally, an additional component of drag is modeled which accounts for other drag sources such as spray. This component is empirically based on Series 64 data and other forms with spray formation. All these components of drag respond to changes in the hull form and so make TSD a tool that can also be used with an optimization code.

TSD has recently been updated to merge some features of FKS (Fourier-Kochin, Steady flow) including the capability to use corrected source strength for wave resistance evaluations. Results shown in the validation section below indicate that this is important for resistance of high speed slender hull forms.

VERES

VERES is a strip-theory ship-motion prediction code, developed by MARINTEK (Norway) as part of their SHIPX package. It implements both ordinary strip theory (Salvesen et al. 1970) as well as the high-speed theory of (Faltinsen and Zhao 1991). It has the capability of handling multi-hull vessel geometry. It includes options to calculate global wave-induced loads at defined cuts, as well as local slamming loads, with appropriate post-processing. Motion control using fins is also an option. A postprocessor is used to derive useful statistical information in random seas. The structural loads on a hull include both global (main hull girder) and local (pressures, including slamming) loads. For conventional monohull surface ships the primary interest is in the vertical bending moment and its distribution along the ship's length. Another area of interest for this type of hull is the local load caused by impact of the hull on the water surface, typically after bottom emergence has occurred. In the case of high-speed, multihull vessels, the loading becomes more complicated. Lateral loads that cause racking between the hulls may be a primary concern, and slamming loads may involve portions of the hull structure that are above the static waterline at rest. Furthermore, the use of high-strength, light weight hull materials will be indicated for HSSL-type hulls, which may result in flexible structures that may vibrate in response to wave impacts (whipping). These issues are being addressed using both VERES and AEGIR calculations.

AEGIR

AEGIR is a unique hydrodynamic code that has a number of advanced numerical features. It is not a traditional panel method, but rather it employs a NURBS based high-order boundary element method (BEM) that uses CAD generated geometry directly in the hydrodynamic boundary value problem. The free surface and wetted body geometry setup are completely automated and require minimal intervention from the user. AEGIR's high-order free surface discretization also has been proven numerically stable through a range of operating conditions and avoids the problems common to low-order methods (Kring Milewski and Fine, 2004; Kring et al., 1999). The boundary conditions in AEGIR can be imposed in either linear or nonlinear form, which leads to a great deal of flexibility in applications including effects such as lifting surfaces, propulsors, shallow water, and maneuvering. It also has a proven, stable time-domain integrator for the equations of ship motion. So, in conjunction with suitable external, nonlinear engineering models (e.g. viscous roll damping), it can act as an efficient flight simulator for advanced marine vehicles. This flexibility allows AEGIR to examine structural wave loads and significant nonlinear effects. The structural loads may be global bending moments and shear forces defined at arbitrary cuts, or they may be local pressure loads that feed directly into structural analysis programs. AEGIR also can compute relative motions as a predictor of slamming, and it can be developed to include models for the secondary slamming loads.

The steady state solver in AEGIR was demonstrated for the HSSL hull forms. This adds capability for the HSSL designer since it goes beyond TSD0 by solving for dynamic sinkage and trim, hull interaction, and a more exact transom formulation. These proved to be very important effects in the HSSL designs. AEGIR demonstrated linear ship motion theory for the variety of HSSL hull forms with full interaction between demihulls, shallow water effects, and hydrodynamic proximity interaction between the HSSL hull and other ships. AEGIR is the only tool in the HSSL suite that can solve the motion problem consistently from zero to high forward speed. It is also capable of handling the difficult following seas problem through zero-encounter frequency. This will be important for the port entry problem and also for load transfer at sea, for instance. The global load prediction was demonstrated for HSSL hulls. Relative motions for slamming were also added to the code, and the slamming forces will be validated in Phase II. For maneuvering, AEGIR will have a more limited role than CFDShip, but the ability to model unsteady lifting surfaces was demonstrated.

CFDShip-Iowa

CFDShip is a general-purpose research URANS CFD code developed at UI over the past ten years for support of student thesis and project research at UI as well as transition to Navy laboratories, industry, and other universities. CFDShip V3 is based on a free surface tracking approach for prediction of free-surface flows at low to medium Froude number. This version has been used to predict pitch, heave, and roll decay motions; wave induced separation for a surface piercing hydrofoil; hull form optimization for a bow wave, sonar dome vortices, and transom wave minimization; propulsor-hull interaction studies; static maneuvers; and shallow water computations, among other topics.

Version 4 code technologies (Wilson et al., 2004; Carrica et al., 2006) include: single-phase level-set free surface modeling for high speed flow; static overset grids for complex geometries and local refinement; blended k-ω and detached-eddy-simulation (DES) turbulence models; higher-order finite-difference discretization, advanced iterative solvers (PETSC toolkit); high performance computing using an MPI-based domain decomposition approach; incident waves; and prescribed 6DOF motions. With the current version of the code, prediction of unsteady loads has been demonstrated for SS4 for the forward speed diffraction problem for head seas at medium high speed (Fr=0.41) for a surface combatant. High speed (Fr=0.62) unsteady breaking bow and transom waves have been demonstrated for the Athena research vessel. It was shown that the use of overset refinement blocks was required to accurately resolve the wide range of physical scales associated with the free surface from the overturning bow wave sheet (~$10^{-4}L$) to the scale of the Kelvin wave pattern (~2L). Also, high speed flow around the Wigley hull (up to Fr=0.99) was simulated with deep and shallow water.

The HSSL project is the first time that CFDShip has been applied to high-speed multi-hull cases. During Phase I, UI extensively developed the code and implemented numerous applications. For ship motions, arbitrary heading, regular and irregular, unidirectional and multidirectional waves were implemented. To allow for the computation of large-amplitude motions a dynamic overset grid technology was used. This was accomplished using the interpolation tool SUGGAR (Noack 2005). The implementation was validated for DTMB 5512 in regular head seas free to pitch and heave. For sinkage and trim calculations, artificial damping coefficients were used and validated for DTMB 5512. For fully appended ships overset grids over solid surfaces were used, which requires the evaluation of the weights of the different active cells that overlap over the solid surfaces. This was implemented as preprocessing steps using the code USURP (Boger, 2006). The new capability was tested for a fully appended Athena R/V with stabilizers, rudders, skeg, shafts and struts. For massively separated flows, a DES model was implemented. This was tested for Athena R/V, both bare-hull and fully appended cases. For full-scale computations, wall functions were implemented. Currently, UI is in the process of implementing water-jet propellers and screw propeller models, and multiple independent/dependent objects (ship-ship interaction, active control surfaces, at sea loads transfer). Initial simulations have produced results for HSSL demihull with water jet, and Athena with screw propeller using body force model. Multiple ship-ship interaction simulations have also been carried out for two independent DTMB 5512, one following the other, in SS6 irregular head waves. In addition, a new numerical towing tank for predicting the full-resistance curve with sinkage and trim by very slow acceleration, tested for Athena, has been implemented for the HSSL geometries.

DEMONSTRATION OF COMPUTATIONAL TOOLS

The tools being developed for the HSSL project will allow designers to predict hydrodynamic properties of high-speed multi-hull vessels in advance of model testing. Predictions include resistance, propulsion, flow, ship motions, maneuvering, and sea induced loads. The suite of codes has already been applied to a variety of hull forms under previous efforts for conventional and even multi-hull ships. The main effort discussed here involves assembling, demonstrating, and evaluating the suite of hydrodynamic tools for high-speed multi-hull HSSL concept designs. Comparisons are made between the various codes to demonstrate the impact of using simpler physics models. Flow details are also shown where appropriate for better understanding of the hydrodynamics, which can aid in identifying important areas of concern such as multihull interaction effects.

Resistance

Resistance is often the first thing evaluated during a hull design and thus is very important as it is a deciding factor early on in the design stage. For resistance evaluations, calculations are performed in calm water over a range of speeds. The current area of interest for HSSL is in the Froude number range of approximately 0.25 to 0.75. Enough different speeds need to be computed to characterize the resistance curve and identify sensitive areas where resistance changes rapidly with Froude number. TSD is the fastest code of this effort for resistance predictions and thus an ideal choice to quickly evaluate a variety of hull concepts. TSD0 and AEGIR provide wave resistance and the total resistance can be estimated using the ITTC approximation for frictional resistance. CFDShip also provides the resistance data with a direct computation and no estimates are needed for frictional or transom resistance. CFDShip has capability to simulate the full resistance curve (Fr=0-1) with sinkage and trim in a single run. It is possible to perform the computations and evaluate differences by computing the concepts with static sinkage and trim over the speed range. However, the sinkage and trim has a significant impact on resistance as shall be seen.

Fig 6 shows wave resistance coefficients (C_R) values for catamaran and its demihull predicted by the different codes. TSD1 includes the effect of single iterative correction to the slender-ship source strength. By including more physics with the 1 iteration approach the absolute values for resistance are dramatically different than with the 0^{th} order approach (TSD0). Both TSD1 and AEGIR show good comparison with CFDShip, particularly for Fr > 0.45. TSD0 substantially under predicts C_R.

Fig 7 compares C_R, friction resistance coefficient (C_F), and total resistance coefficient (C_T) for both the catamaran and its demihull using CFDShip results. C_F agrees well with the ITTC (1957) friction line. Also included in Fig 7 are C_T values for static cases (without sinkage and trim) run for Fr=0.55 to show the effect of sinkage and trim on resistance. Results show 13% and 7% decrease for catamaran and demihull, respectively compared to values with predicted sinkage and trim. The interference factor (IF = (C_{Rcat} - C_{Rdemi}) /C_{Rdemi}) was calculated over the entire Fr range with predicted sinkage and trim (Fig 8). The catamaran sinkage and trim have higher magnitudes compared to the demihull, and the difference in sinkage and trim between the catamaran and the demihull is proportional to IF. Correlations between IF and variation in sinkage & trim were investigated by scaling the differences in sinkage and trim between the two cases as shown in Fig 8. The scaled variation in trim angle ({catamaran – demihull} x 50) correlates well with IF curve. The scaled variation of the sinkage ({demihull – catamaran} x 500) correlates moderately well with IF curve. Wave interference magnifies the bow wave elevation between hulls increasing leading edge hull surface pressure, and also magnifies the trough depression decreasing trailing edge hull surface pressure. This increases the trim angles proportionally, and hence we see the correlation between interference factor and variation in trim. Apart from being influenced by IF, the sinkage and trim in turn influence IF due to strong coupling between the two. This is evident from the 16% decrease in IF for cases run with fixed static sinkage and trim (IF=0.5 with S&T, and IF=0.42 w/o S&T at Fr=0.55). Note that in Fig 7, caption unsteady RANS refers to the numerical towing tank technique used to get the full curve in a single run. Steady RANS refers to prediction of sinkage and trim at one particular Fr.

The resistance curves show distinct humps at about Fr=0.5 and 0.55 for catamaran and trimaran, respectively. The hump is not as distinct for the demihull. Fig 9 shows the trimaran surface pressures and wave elevation for three Fr (0.45, 0.55, 0.65) corresponding to the beginning, peak, and past the hump. High suction pressure due to wave trough interference over the entire trailing end of the ship cause the resistance peak for Fr=0.55. For Fr=0.45 the suction pressures aren't as high, and for Fr=0.65 the region of wave trough interference overshoots the stern with decreased effect on the hull surface.

Powering

To demonstrate the ability to predict powering a computation of the trimaran demihull concept is performed with the waterjet. The waterjet is included in the calculation through the computational grid. This includes inlet and nozzle details from which efficiencies can be obtained from the computation. The pump is not modeled in detail, but approximated with an actuator disc with a prescribed body force. To achieve self propulsion at a particular speed the body force applied via the actuator disc is iterated against the computed resistance of the hull till the two matches. Because the waterjet is included as part of the computation the flow through the waterjet is computed directly to provide propulsor/hull interaction and above water discharge. Initial computations showing the flow through the inlet and exiting with above water discharge are shown in (Fig. 10).

Motions

For seakeeping evaluations the primary early design tool is VERES due to its computation speed. The calculations performed using VERES here are entirely linear frequency domain calculations. Fig 11 and Fig 12 show predicted heave and pitch RAO's in head seas. . Another factor examined was the influence of including the steady dynamic sinkage and trim. When this is included the underwater geometry about which the solution is linearized is adjusted by dynamic draft and trim. VERES does not predict sinkage and trim so these values must be provided either from model tests or from an AEGIR or CFDShip calculation. Shown in Fig 13 is the comparison of the predicted heave and pitch RAO's for the HSSL catamaran using both the static draft and trim and the dynamic draft and trim computed by AEGIR. The differences between the two solutions is significant and O'Dea (2005) showed improved correlation between VERES and model test data when the dynamic sinkage and trim was included in the calculations.

AEGIR has both steady-state and a time-domain formulation. The steady-state formulation is used to efficiently compute sinkage, trim, and wave resistance. These steady results are important precursors to the seakeeping problem. For seakeeping, AEGIR use a purely time-domain approach, so RAO's are obtained by analyzing the time response of a ship either from a series of regular wave runs or from a single irregular wave run. Both seakeeping methods, VERES and AEGIR, were used by NSWCCD in the course of this project. Fig 14 is an illustration of a typical wave pattern snapshot for an HSSL catamaran in oblique seas. This case was for the HSSL catamaran operating in Sea State 6 at 43 knots. All runs were performed using a ship speed of 43 knots, which is the desired transit speed for the HSSL vessels. AEGIR simulations have been performed for the HSSL catamaran at 43 knots in head seas and bow quartering seas. The VERES analysis was performed at all headings from head seas to following seas in 15° increments. In Fig 15 and Fig 16 a comparison of the pitch and heave RAO's in head seas is shown.

A number of unsteady simulations have also been performed with CFDShip to help understand flow physics. For trimaran, motions calculations in SS6 for 0^o heading in regular waves, and 45o and 135^o in irregular waves are performed. Ship speed was reduced to 20 Knots for 135^o case to allow the waves to overtake the ship. Fig 17 shows the pitch, heave, and roll motions for the unsteady cases with corresponding resistance. Fig 18 shows the elevation on the trimaran at the two extremities of pitch angles for 0^o heading. Fig 19 shows peak hull pressure at the instance when slamming occurs. Fig 20 and 21 shows the free-surface elevation and boundary layer for trimaran at 45^o, and 135^o heading respectively in irregular waves.

Loads

VERES and AEGIR were also used to compute the global seakeeping loads on the HSSL catamaran. Loads calculations for the trimaran will be performed in Phase II. In order to compute the seakeeping loads a mass distribution must be defined in both codes using a cloud of point masses. A simple mass distribution using 200 point masses was determined which matched the total mass of the HSSL catamaran and collectively provided the correct roll, pitch and yaw gyradii. Fig 22 shows a comparison of the vertical bending moment RAO for the HSSL catamaran at a position 75.9 meters forward of the transom in head seas at 43 knots predicted by VERES. VERES results are shown based on both the static trim and incorporating the dynamic sinkage and trim predicted by a steady AEGIR run. CFDShip provides keel slamming loads during water reentry. For trimaran at 43 knots in regular SS6 waves, a maximum slam pressure of 38 psi occurs at x/L =3.75 during reentry (Fig 19).

Added Resistance

For added resistance in waves and determining delivered power in waves the basic calm water resistance and powering computations are again performed in head seas with the models free to pitch and heave. For HSSL the sea states of most interest are SS4 through SS6. These computations are typically done through SS4 up to full power speed for operability, and through SS6at reduced power For the HSSL concepts of interest it is not expected that sea states below SS4 are of interest and thus do not need to be examined. These predictions, which are again done using CFDShip, allow designers to understand how much thrust needs to be added to overcome the wave field. The seakeeping predictions allow them to decide if it is safe to compensate with added throttle for such conditions.

Unsteady calculations were performed for the multihulls with regular incident waves with the hulls fixed (diffraction) or free to move in response to the waves to demonstrate CFDShip's ability to simulate such flows and as a mechanism to provide added resistance. For the regular incident head wave, a nondimensionalized amplitude corresponding to a SS6 wave height and a wave length of 1.411 ship lengths is used. Approximately 100 time steps per period are used in the calculation. The solution is started abruptly, so that a few periods are required before a periodic solution is obtained. The calculated wetted area from several of the catamaran solutions is shown in Fig 23. The dashed line shows the static design area and the solid black line shows that the wetted area decreased for the steady calm water flow. For the diffraction problem, the wetted area oscillates about the calm water results with maximum amplitude about 20% greater, as seen by the blue curve. When the catamaran is free to pitch and heave the area oscillates with maximum amplitude about 85% greater than the calm water wetted area. From the area vs. time plot, periodicity occurs after about 4 or 5 incident wave periods. The resistances vs. time results are also shown in Fig 23. Again, the steady state calm water resistance is shown as the solid black line. Even though the diffraction solution has not yet obtained periodicity, the solution indicates a linear type response to the regular incident input wave. The oscillating force appears greater than the steady state force. The nonlinear response of the pitching and heaving catamaran is seen by the red curve, where multiple oscillations occur per one period of the incident wave.

Fig 24 shows details of the pitching and heaving catamaran for approximately one period of motion as a function of iteration number. Constant time steps have been used in the calculation. Fig 25 shows three particular instances of a half period – minimum and maximum wetted area and a position in between. Iteration numbers will be used to identify these positions. The figures in the right column show pressure contours on the wetted portion of the hull. When the wetted area is at its minimum, near step 550, the pitch is close to its greatest bow up position at nearly 6^{o} and the heave is at its maximum of 0.04L. A trough of the incident wave is beneath the bow at this point. Both the pitch and the heave will begin decreasing at this point. At iteration 580, at approximately ¼ period, the wetted area is about the same as its static or calm water. At this point, the vertical displacement is almost zero and still decreasing, while the pitch has nearly reached its most bow down position at approximately -2^{o}. At step 610, the wetted area is at its maximum and the vertical displacement is near its maximum downward position of -0.04L. The pitch is zero, but increasing. At this point, a crest of the incident wave is at the bow of the boat.

The added powering required due to waves can also be predicted with CFDShip by performing the powering computation discussed earlier in head waves. An example of the computation of the Trimaran demihull in head waves of SS6 is shown in Fig 26. The above water discharge of the jet is clearly shown in the figure and such capability will also allow one to fully determine if air entrainment into the propulsor becomes an issue due to draw down near inlet in various sea state conditions.

Operability

Once the linear RAO's are determined at the speeds and headings of interest, the VERES post-processor can quickly and easily generate plots showing motions, velocities and accelerations at specified points, as well as statistics such as slamming probability, probability of green water on deck, motion sickness incidence, motion induced interruptions per minute, etc. The user can define the locations where these values will be predicted and the properties of the sea state. A few of the plots generated by VERES for the HSSL catamaran and trimaran hulls are provided here. Fig 27 shows the VERES prediction for Motion

Sickness Incidence (MSI) on the HSSL trimaran concept at 43 knots with various headings in a sea state defined with a Bretschneider spectrum with 4 meter significant wave height. Fig 28 shows the VERES prediction for incidence of slamming on the centerline of the wetdeck of the HSSL catamaran concept at 43 knots with various headings in a sea state defined with a Bretschneider spectrum with 4 meter significant wave height. Results can also be show as operating limits. These limits indicate the maximum significant wave height in which the ship can operate at a specified speed and heading without exceeding criteria specified by the user. Another feature available in VERES is the use of passive or active appendages to reduce the motions (ride control). This is expected to be a necessary part of HSSL designs. To demonstrate the influence of passive and active ride control, a VERES analysis was performed using the HSSL catamaran with retractable T-foil deployed along the centerline of the vessel 140 meters forward of the transom and small trim tabs placed on the transom of each demihull. . The analysis was performed both with the foils fixed and with active ride control. Fig 29 and Fig 30 show the influence of both passive foils/tabs and actively controlled foils/tabs on the limiting significant wave height curves based on the criteria that the motion sickness incidence must be less than 25% at the CG, and the motion induced interruptions must be less that one per minute at the CG.

Maneuverability

PMM simulations demonstrated CFDShip's capability to predict the forces and flow field about the HSSL catamaran resulting from prescribed planar maneuvers in calm seas and in regular incident head waves. The sway and yaw motion given by sway = 0.07218 sin(2.039 t) and yaw = -8.4 cos(2.039 t) is shown in Fig 31. About 160 time steps per period were used. (The motion was started abruptly, so that some transients will likely appear in the results.) The hull is in the fixed static orientation. For the head wave case, a regular wave with ak = 0.025 was imposed. The plots on the right side of Fig 31 show the calculated yaw moment and lateral force for three periods of the prescribed planar motion. The solid black curves show the results for the maneuver in calm seas and the dashed red curves show the results in head waves. The calculations show that extreme side forces and yaw moments occur at the extreme sway locations, where the turning is the greatest, and the least occur when the boat is crossing the centerline of the maneuver. The incident waves have a large effect on the lateral forces – at some places doubling the magnitude and other places changing the direction. The figures on the left illustrate the flow field when the boat is just moving across the centerline (upward in the figure). The large asymmetric bow wave can be seen due to the forward and sideward motion plus the turning at the bow. The bottom figure illustrates the vorticity created by a combination of the sideward motion and the rotation of the boat. At this instant, vorticity can be seen on one side of the boat in the forward region and counter rotating vorticity on the other side in the aft region.

VALIDATION

The codes being used have already been applied to a large variety of hull forms. Test data is required for validation of the tool set to provide confidence in the accuracy of the predictions. Table 4 provides a list of data needed for individual code validation. Ideally, a comprehensive set of data is needed for hulls that are similar to those of interest to the HSSL project. Such comprehensive data sets do not exist due to the diverse nature of the data required and the hull forms of interest. However, several sets of data exist which in aggregate are sufficiently comprehensive to provide validation without additional model testing.

Data Available for Validation

Table 5 gives a partial summary of data available. While each of these data sets have value for use in validating design tools, some offer greater utility than others. For trimaran, model 5594 (Fig 32) with side hulls was chosen as the validation case (Kennell, 2004; Salgado and Mutnick, 2002)), due to unavailability of data for equal hull trimarans. Model 5594 is a very slender high speed trimaran hull form with sidehulls contributing less than 2% of total displacement. Resistance, and sinkage and trim over full range of speeds along with wave cuts for 55 knots will be used for validation of calm water runs. Motions and slam loads for 55 knots at different heading and sea states will be used for validation of rough water runs. For catamaran, model 5228 and model series 1-6 (Molland et al, 1995; Molland et al, 2001) were chosen for validation. Model 5528 is a catamaran with asymmetric demihulls. Data sets exist for free running self propelled tests. There is also a calm-water powering report (Kelley and Oliver, 1970) for 5228, which includes EHP, SHP, and side forces between hulls, wave profiles both inboard and outboard, for 4 lateral spacing. The quantities measured for Model 522 are Heave, Pitch, Roll, Absolute Bow & Stern Motion, Relative Bow Motion, Added Thrust in waves, Loads between hulls: Shear and Transverse Force, Bending Moment: Vertical, Torsion and Yaw for Fr= 0.0, 0.156, 0.312 at 5 different headings from 0^o to180^o. Molland et al, (2001) conducted experiments for series of models (Model 1-6) and measured Heave, Pitch, Roll, Forward and mid Acceleration, Added Resistance in Waves for Fr= 0.2, 0.5, 0.8 (and 0.65 for oblique waves) at headings 120, 150, 180 for two different hull spacing S/L = 0.2, and 0.4. Model 372 is a high-speed catamaran hull designed and tested at Delft University (van't Veer 1998a, 1998b). Calm-water results include resistance, sinkage and trim and wave profiles up to Fr = 0.75. The model was tested in regular head and bow waves to obtain heave, pitch and load RAO's. The test program also included forced-oscillation tests to measure hydrodynamic components (added mass, damping).

Current Validation Status

Preliminary validation studies were carried out using model 5594. Fig 33 compares TSD resistance to EFD. Note the effect of sinkage and of source strength correction (labeled 1it, for one iteration). Fig 34 shows preliminary results from resistance curve and Sinkage & Trim validation for CFDShip. Comparison of the wave cuts at y/L=0.081, 0.102, and 0.294 at Fr=0.51 (55 knots) shows good qualitative agreement (Fig 35). However, results show need for a finer grid to improve predictions of lower wavelengths and the wake regions. Initial analysis of slam loads (45 knots, SS6) at location corresponding to EFD (Simone and Brady, 2004) pressure taps (Fig 36) show reasonable agreement (CFD=5.4 psi, EFD= 6.6 psi). However, CFD run times were much lower (4 ship length flow time) compared to EFD and longer runs are needed.

CONCLUSIONS

The challenges posed by high-speed ship design in determining naval architectural parameters for the often-unconventional hull forms were tackled by a synergetic team of highly experienced navy architects, code developers, and hydrodynamists by creating a design suite to assist ship designers predict resistance, propulsion performance, seakeeping, and maneuvering in all stages of the design process. This massive undertaking was divided into two phases. Phase I involved initial HSSL concept development and assembling the hydrodynamic tools with initial evaluation and validation to demonstrate capability in meeting the naval architect's needs. Phase II involves implementation of design suite to explore concept performance through parameter ranges of interest to the ship designers and detailed validation.

The hydrodynamics tools proved capable in meeting naval architect's needs and critical aspects regarding hull interactions, resistance, and seakeeping were identified. TSD, AEGIR and CFDShip were used to predict resistance over entire range of speeds. Wave interaction effects were studies using CFDShip results. To demonstrate the ability to predict powering, computations of the trimaran demihull concept was performed with the waterjet in calm and rough seas using CFDShip. A number of unsteady simulations in regular and irregular seas at arbitrary heading have also been performed with CFDShip to help understand flow physics. PMM simulations demonstrated CFDShip's capability to predict the forces and flow field about the HSSL catamaran resulting from prescribed planar maneuvers in calm seas and in regular incident head waves. VERES and AEGIR performed sea-keeping calculations using linear frequency domain approach, and time-domain approach, respectively. AEGIR simulations have been performed for the HSSL catamaran at 43 knots in head seas and bow quartering seas. The VERES analysis was performed at all headings from head seas to following seas in 15° increments and post processed results include slamming probability, probability of green water on deck, motion sickness incidence, and motion induced interruptions per minute. VERES and AEGIR were also used to compute the global seakeeping loads on the HSSL catamaran.

Initial qualitative validation of the codes is being performed using critical elements of existing data sets for similar high-speed ships, conventional and multi-hull, as data is not yet available for the HSSL concept. The computed HSSL flow field will help identify important data acquisition locations for future experiment test design of the HSSL concepts. Optimization of the hulls forms is under way. The performance of the optimized HSSL hull forms will be evaluated and compared against the initial HSSL design.

Future Plans (Phase II)

The Phase II effort will largely be a continuation of Phase I, with the same suite of tools, but with a more focused effort on validation of the design suite and detailed evaluation of the HSSL concept performance based on important parameter ranges identified for all disciplines. The hull forms will be optimized. By the end of Phase II, the team would be in a position to demonstrate and validate free model, self–controlled ship capability.

8. ACKNOWLEDGEMENTS

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Table 1 Summary of specifications

PARAMETER	VALUE
Displacement	≤12000 Tons
Length	~560 Feet
Payload	~4000 Tons
Sustained Transit Speed	≥ 43 Knots (presumed Fr > 0.5, multi hull likely)
Unrefueled Range At Transit Speed	≥ 5000 nautical miles
Draft At Port Entry	≤ 6.5 Meters (have to morph to low-draft)
Special Capability Load Transfer	At sea transfer of heavy point loads
Special Capability Air Capable	Weather deck free of obstacles
Full Performance Weather Limit	≥ SS4

Table 2 Hull form optimization objective functions

Test ID	Geometry	Objective function	Geometrical Constraints	Functional constraints
1	**Catamaran**	**Single objective problem:** With $\alpha_i = (1/3, 1/3, 1/3)$, $Fr_i = (0.460, 0.541, 0.622)$ Δ_i = (12000, 10785, 9570) t minimize: $F = \sum_{i=1}^{3} \alpha_i \frac{R_T(Fr_i, \Delta_i)}{V_i^2}$	a. Max overall length (170.7 m) and max beam (40 m) b. Draft ≤ 6.5 m c. Total displacement Δ_i depending on the speed d. $0.3 \le L_{CB} / L \le 0.7$ e. Individual hull waterplane area ≥150 m^2 f. Immersed transom area = specified g. More than 1 m above the keel and from L/2 to stern, the distance between port and starboard shells is ≥ 1 m	None
2	**Trimaran**	**Single objective problem:** min *F as in problem #1*	As in problem #1	None
3	**Trimaran**	**Multiobjective problem:** With *B(bridge)=(128.025, 0, 15) m*, *D(flight deck) = (21.3375, 0, 5) m* and *sea state 5*, minimize: $F_1 = R_T(0.460) + R_T(0.622)$ $F_2 = 0.5\frac{\ddot{z}_B}{0.2g} + 0.5\frac{\dot{z}_D}{1.0}$	As in problem #1	*a.* $\frac{R_T(0.460)}{R_T^{phf}(0.460)} \le 1.0$ *b.* $\frac{R_T(0.622)}{R_T^{phf}(0.622)} \le 1.0$ *c.* $\ddot{z}_B \le 0.2g$ *d.* $\dot{z}_D \le 1.0 m/s$
4	**Trimaran**	**Single objective problem:** With F_1 and F_2 defined in problem #3, minimize: $F = 0.5\, F_1 + 0.5\, F_2$	As in problem #1	As in problem #3

Table 3 Naval architect's need from the computational tools.

	Design Stages (Increasing Precision --->>)		
	Concept Design	Preliminary Design	Functional Design
Resistance and Power			
SS 0 Effective Power	X	X	X
SS 0 Delivered Power	X	X	X
Hull Form Optimization	X	X	X
SS X Effective Power		X	X
SS X Delivered Power		X	X
Motions and Habitability			
Rigid Body 6DOF Motions in Sea States	X	X	X
Operability Evaluation Using Specified Criteria	X	X	X
Loads in Service			
Lifetime Hull Girder Loads	X	X	X
Lifetime Slamming Loads	X	X	X
Lifetime Green Water Loads		X	X
Maneuverability			
Non-Dimensional Stability Indices	X	X	X
Simulation of Standard Maneuvers		X	X

Table 4 Data needed for individual code validation

	Resistance					**Seakeeping**					**Maneuvering**		
	Resistance	Sinkage & Trim	Propulsion	Wave Cuts	Boundary Layer	Motions RAOs	Added Resistance	Primary Loads	Secondary Loads	Roll Damping	Maneuvering Forces	PMM Data	Maneuvering in waves
TSD	X	X		X									
VERES						X		X	X	X			
AEGIR	X	X	X	X		X	X	X	X		X	X	X
CFDSHIP	X	X	X	X	X	X	X	X	X	X	X	X	X
RNN						X				X		X	X

Table 5 Partial list of available data

	Resistance					Sea-keeping					Maneuvering		
	Resistance	S&T	Propulsion	Wave Cuts	Boundary Layer	Motions RAO	Added Resistance	Primary Loads	Secondary Loads	Roll Damping	Maneuvering Forces	PMM Data	Maneuvering In Waves
TRIMARANS													
Dash													
HSS 559[36,37,42]	X	X	X	X	X	X	X	X	X				
USNA[14]	X	X				X	X						
Triton model scale	X	X											
Triron full scale			X			X	X	X	X	X			X
Model 5598													
KMM / CCDoTT	X	X					X						
CATAMARANS													
Delft	X	X		X		X		X					
Kashiwagi						X							
Model 1-6[29, 30]	X	X		X			X						
Model 5596[39]	X	X											
HSV full scale[27]			X			X	X	X	X				X
Model 5228[23]	X	X	X	X			X	X	X				

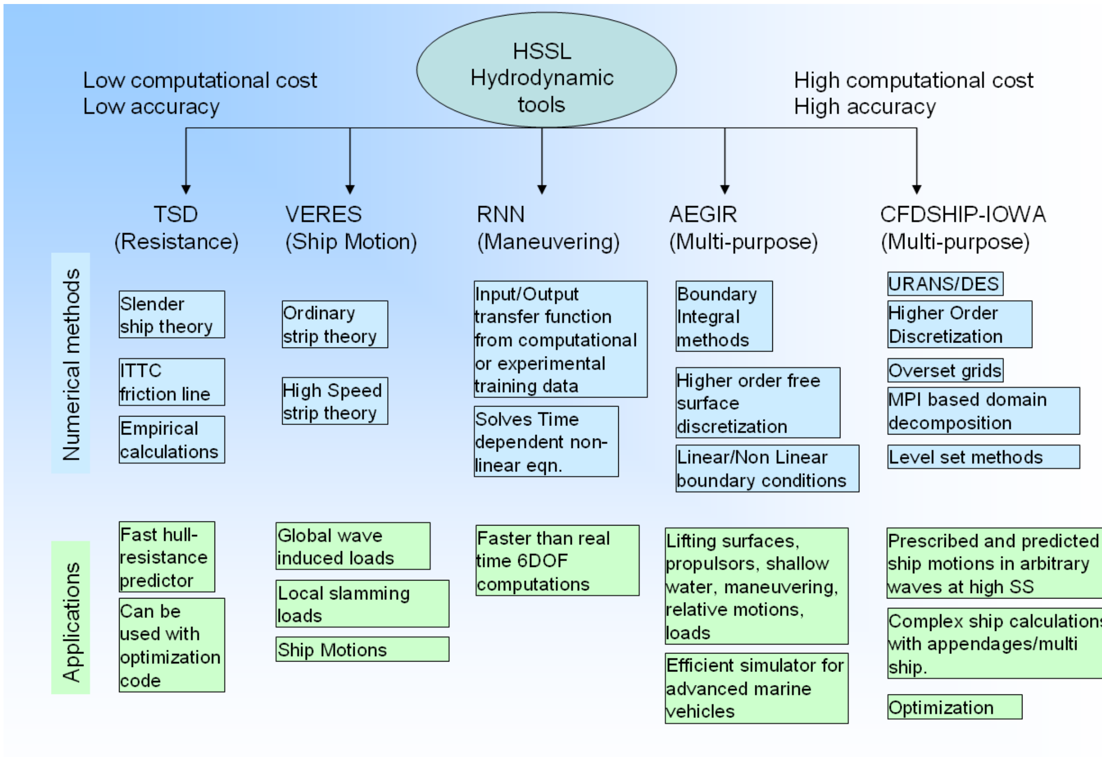


Fig 1 Summary of hydrodynamic tools

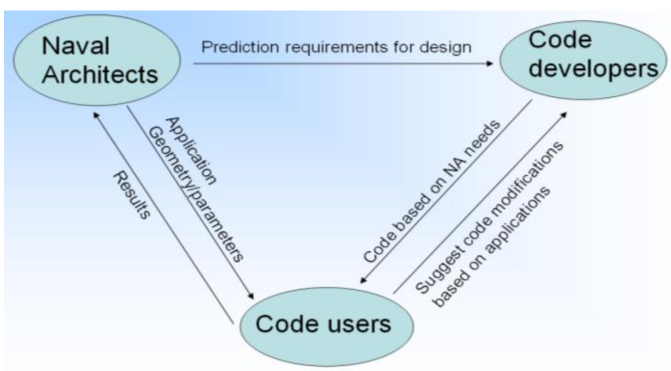


Fig 2 CFD / Ship-hydro synergy

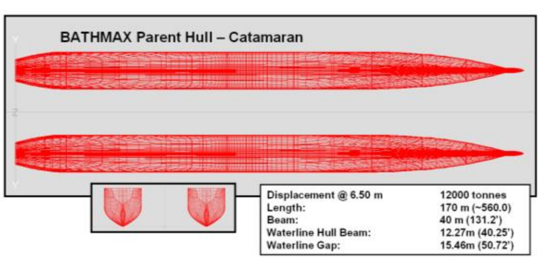


Fig 3 HSSL-B Catamaran

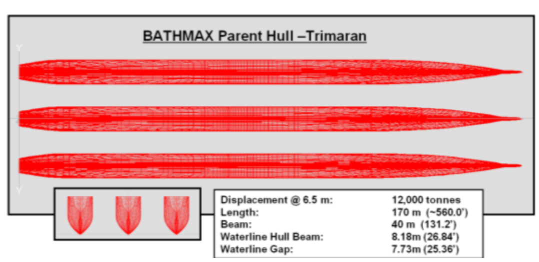
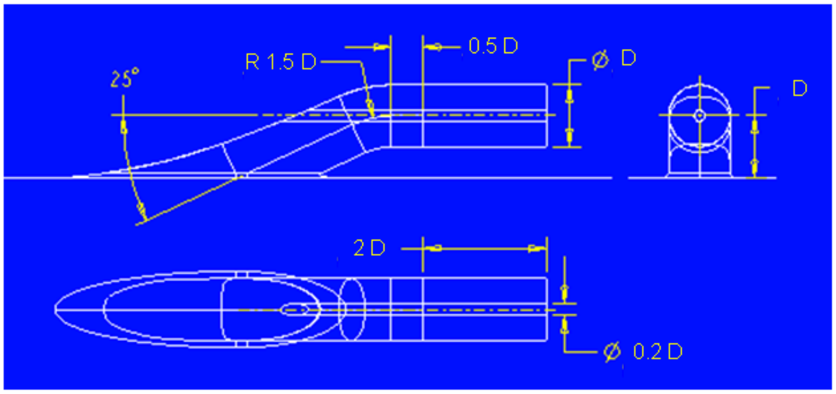


Fig 4 HSSL-B trimaran



IOWA Power Calculation								
Fr	Ct	Ct'	Vk	WS, m2	Resistance, kN	Eff Power, kW	Delivered Power (η = 0.70)	
0.55	0.00470	0.00517	43.6	6929	9249	207,517	296,453	
		(Increased 10%)						
	Waterjet Size Using IOWA Power				$kW = 0.002557 \cdot D^2 \cdot V_k^{1.5}$			
	Lips Waterjet E Series		LJ200E	LJ219E	LJ263E	LJ268E	LJ322E	LJ379E
	Number of Units		10.4	8.7	6.0	5.8	4.0	2.9
	Transom flange Diameter, m		3.4	3.7	4.4	4.5	5.4	6.4
	Waterjet Size Using BIW Power							
	Number of Units		3.6	3.0	2.1	2.0	1.4	1.0
	Transom flange Diameter, m		3.4	3.7	4.4	4.5	5.4	6.4

Fig 5 Water jet concept design

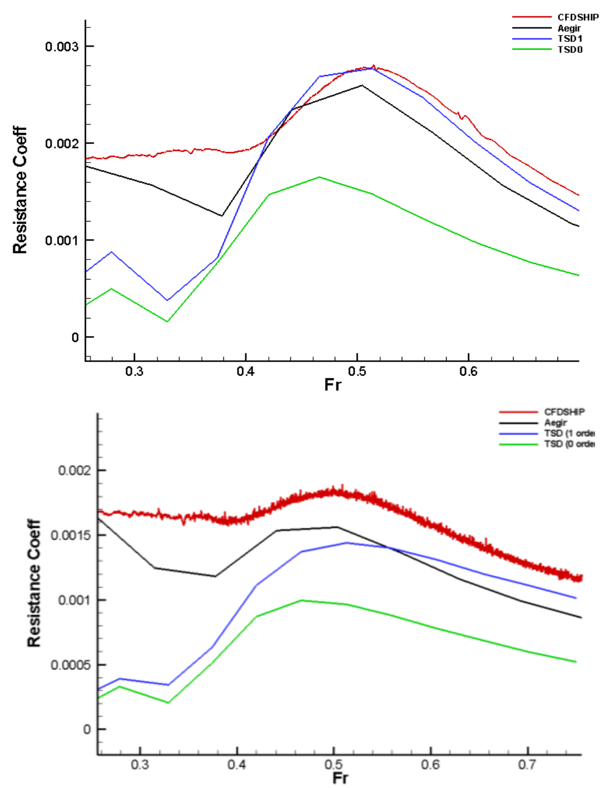


Fig. 6 Wave resistance coefficients for different codes: a) Catamaran, and b) Demihull

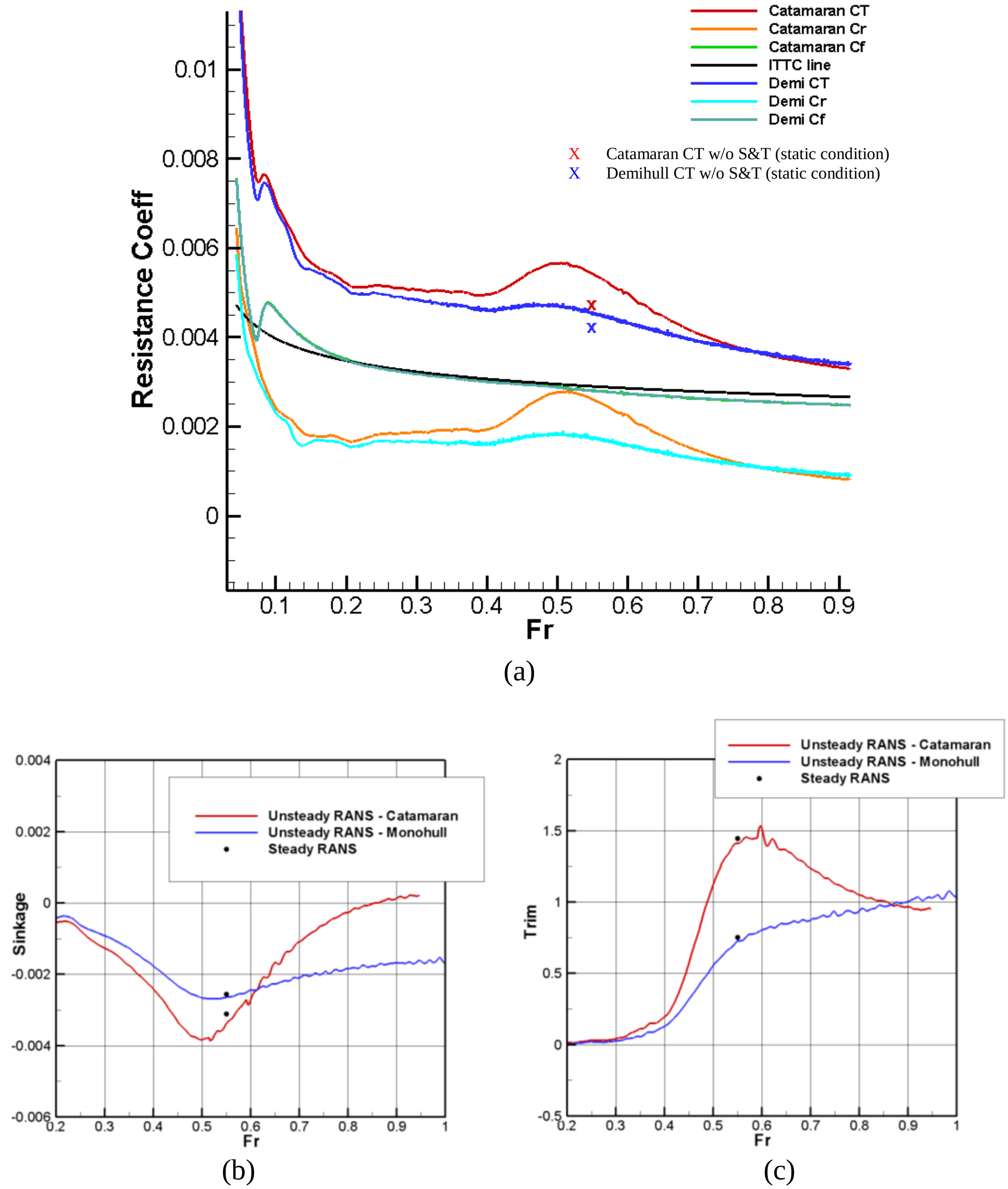


Fig. 7 Catamaran vs. demihull interference evaluation by CFDShip with predicted sinkage and trim over entire Fr range: a) Resistance, b) Sinkage and c) Trim

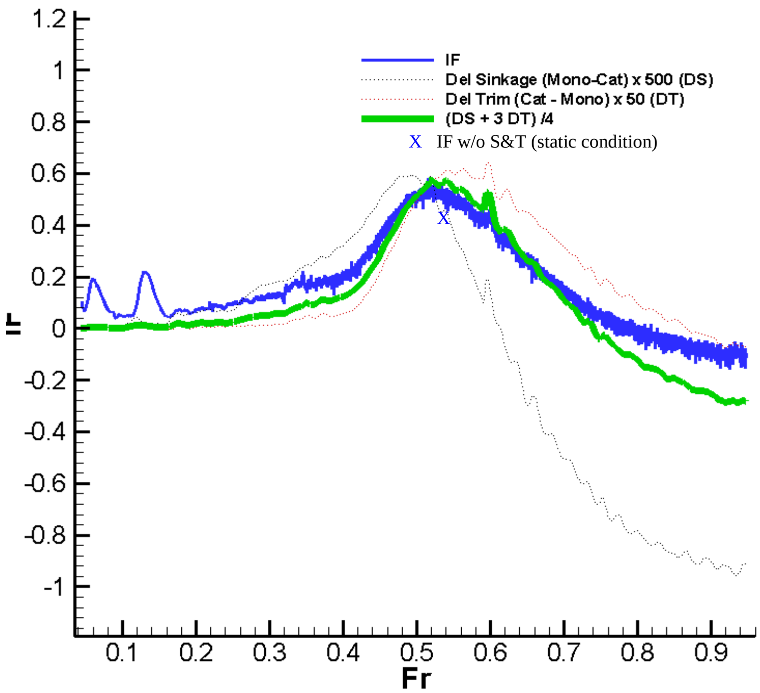
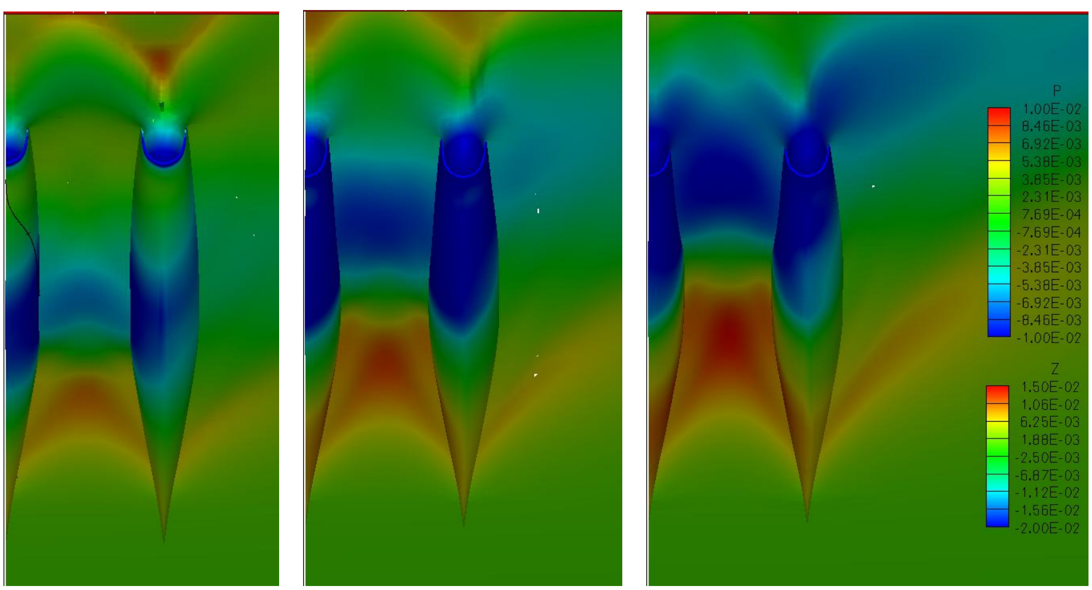


Fig. 8 Correlation between interference factor, and Sinkage & trim from CFDShip



(a) (b) (c)

Fig. 9 Trimaran hull pressures and wave elevation from CFDShip: a) Fr=0.45, b) 0.55, and c) 0.65

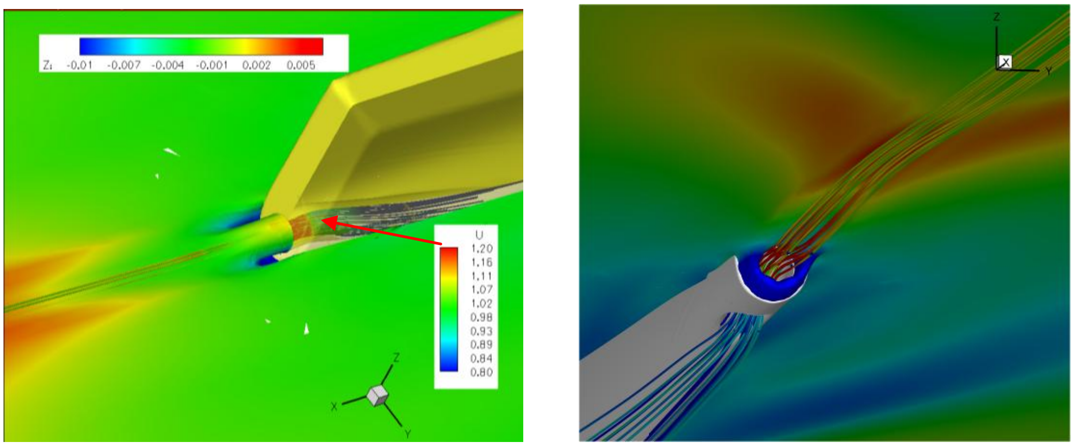


Fig. 10 Free-surface elevation contours, with streamlines inside duct colored by U-velocity from CFDShip

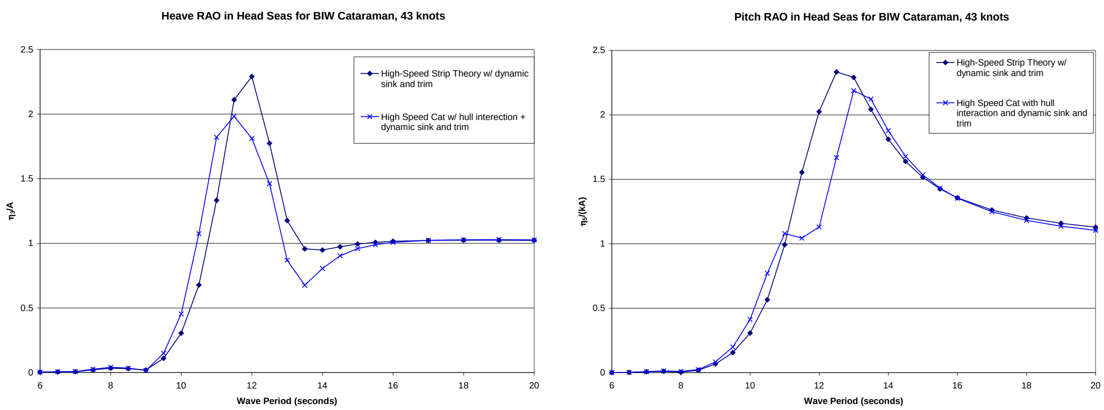


Fig. 11 Comparison of VERES predictions for heave and pitch RAO for HSSL Catamaran at 43 knots in head seas using high-speed strip theory and the theory for a high-speed catamaran with hull interactions.

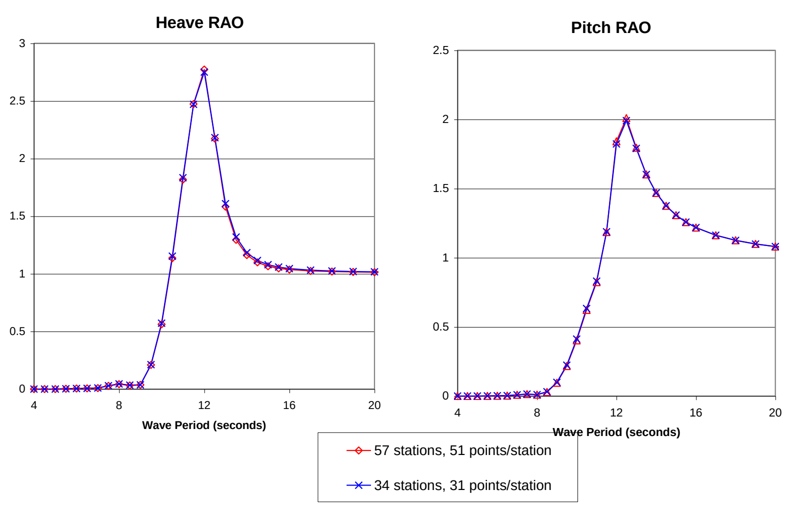


Fig. 12 Convergence of VERES predicted heave and pitch RAO for HSSL catamaran in head seas at 43 knots.

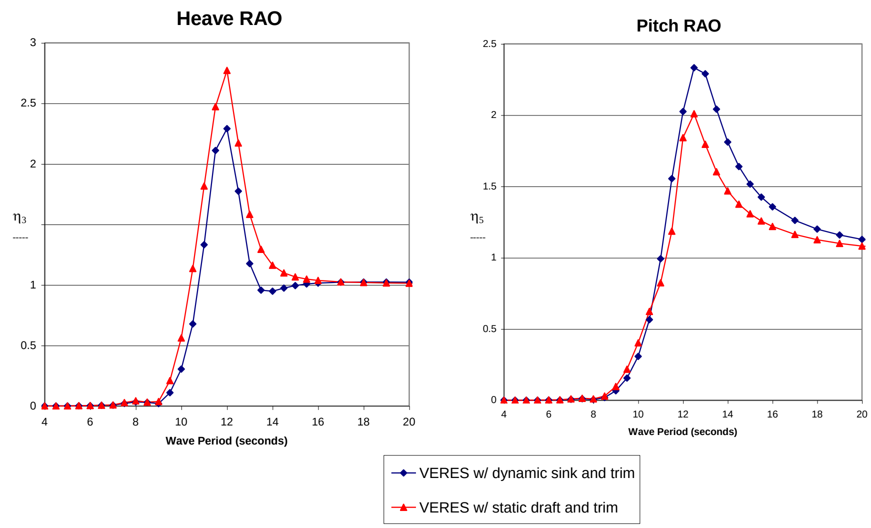


Fig. 13 Influence of including dynamic sink and trim from steady AEGIR run on VERES predictions for heave and pitch RAO's in head seas at 43 knots

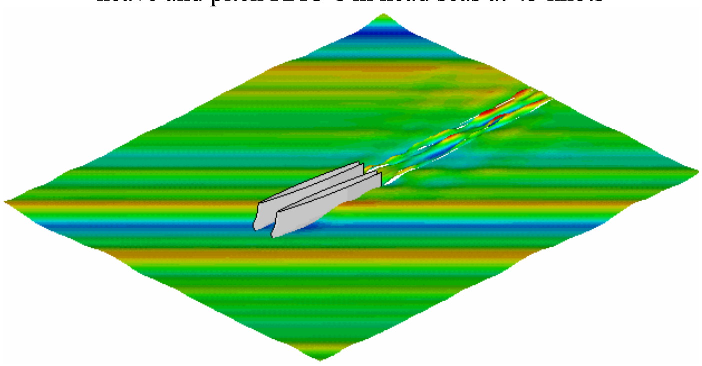
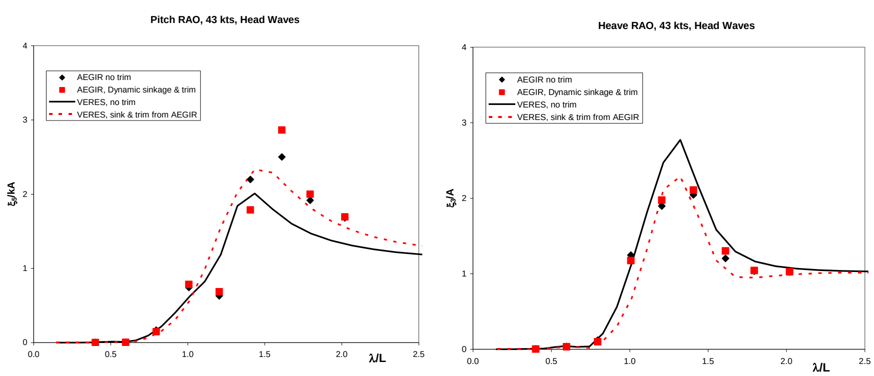


Fig 14 Snapshot from AEGIR of the unsteady wave field and HSSL Catamaran for 43 knots forward speed in bow quartering, Sea State 6 irregular waves.



(a) (b)

Fig. 15 Comparison of predicted Pitch and heave RAO's from VERES and AEGIR for HSSL catamaran in head waves at 43 knots: a) Pitch, b) Heave

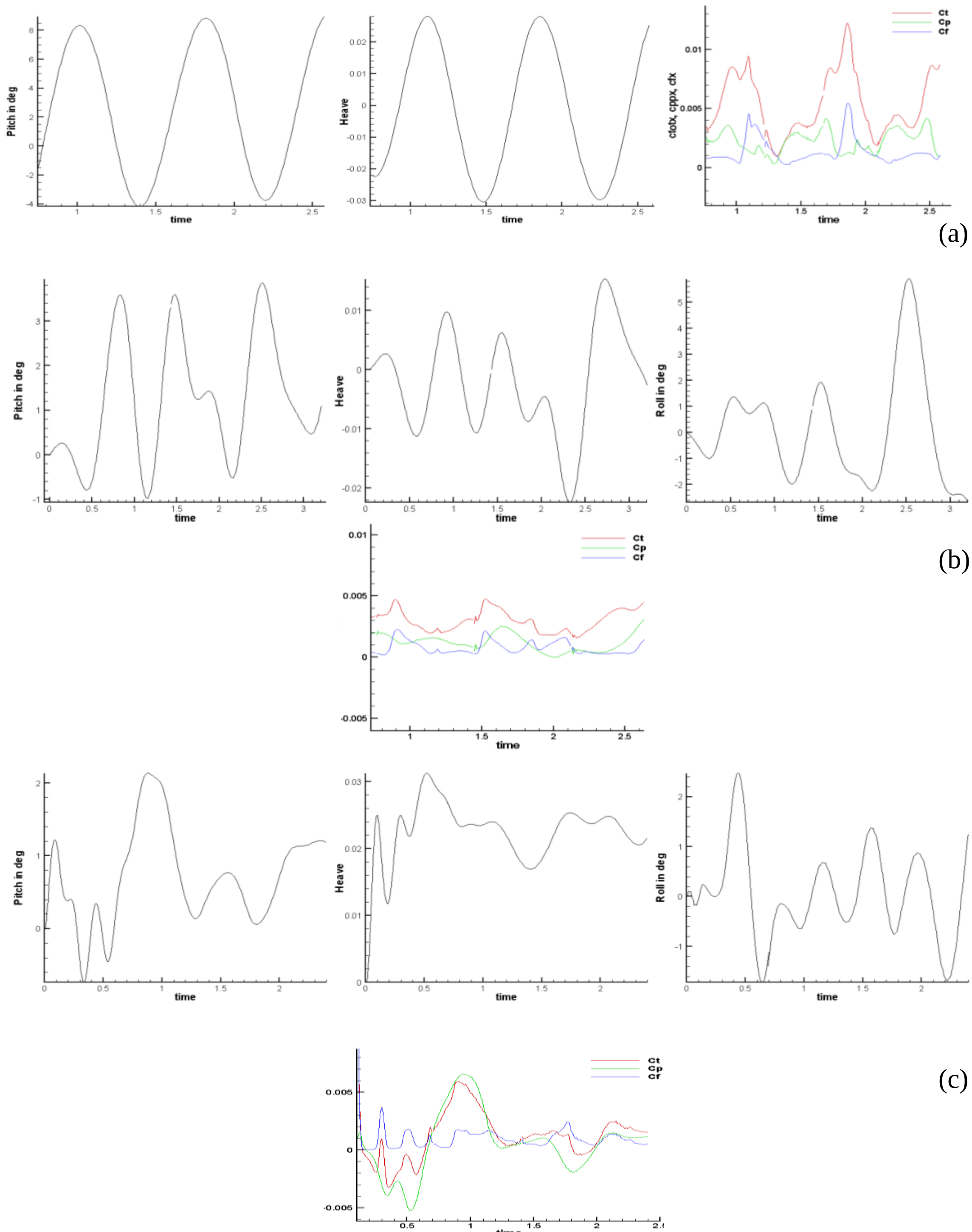


Fig 17 Motions and resistance from CFDShip for a) 0° heading, b) 45 ° heading, and c) 135 ° heading

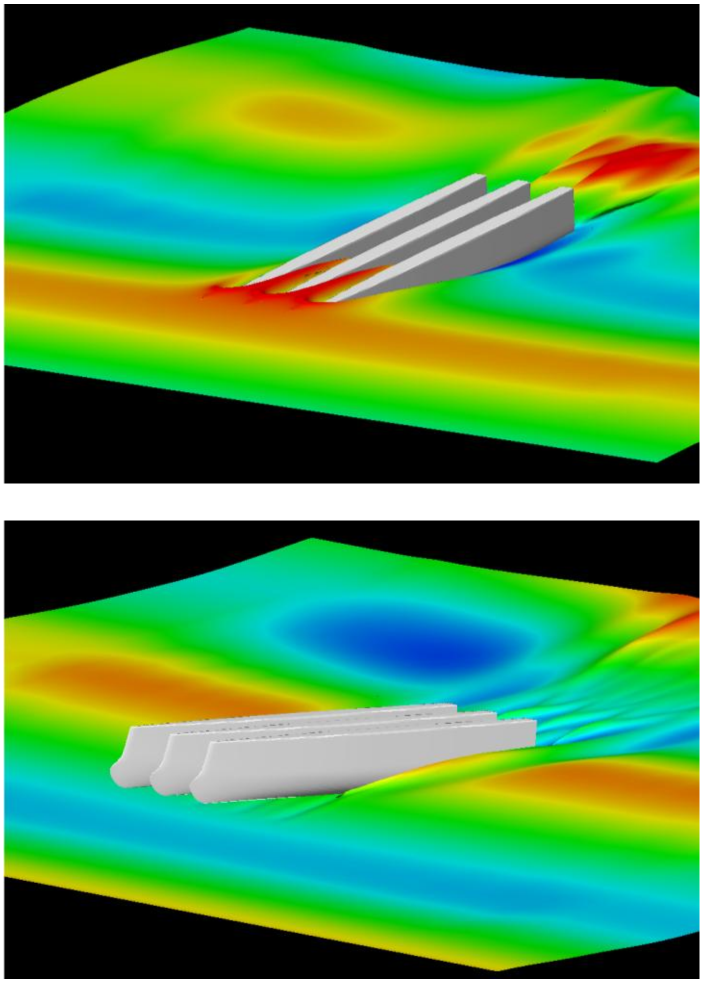


Fig 18 Free-surface elevation at extremities of pitch from CFDShip

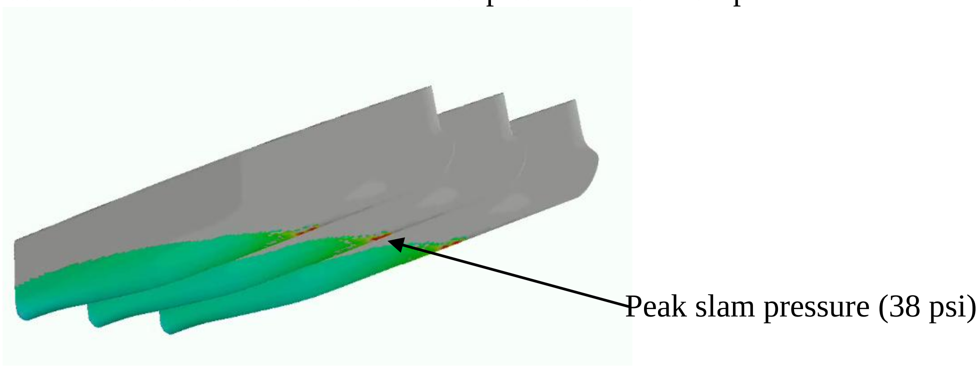


Fig 19 Slam pressure on hull from CFDShip

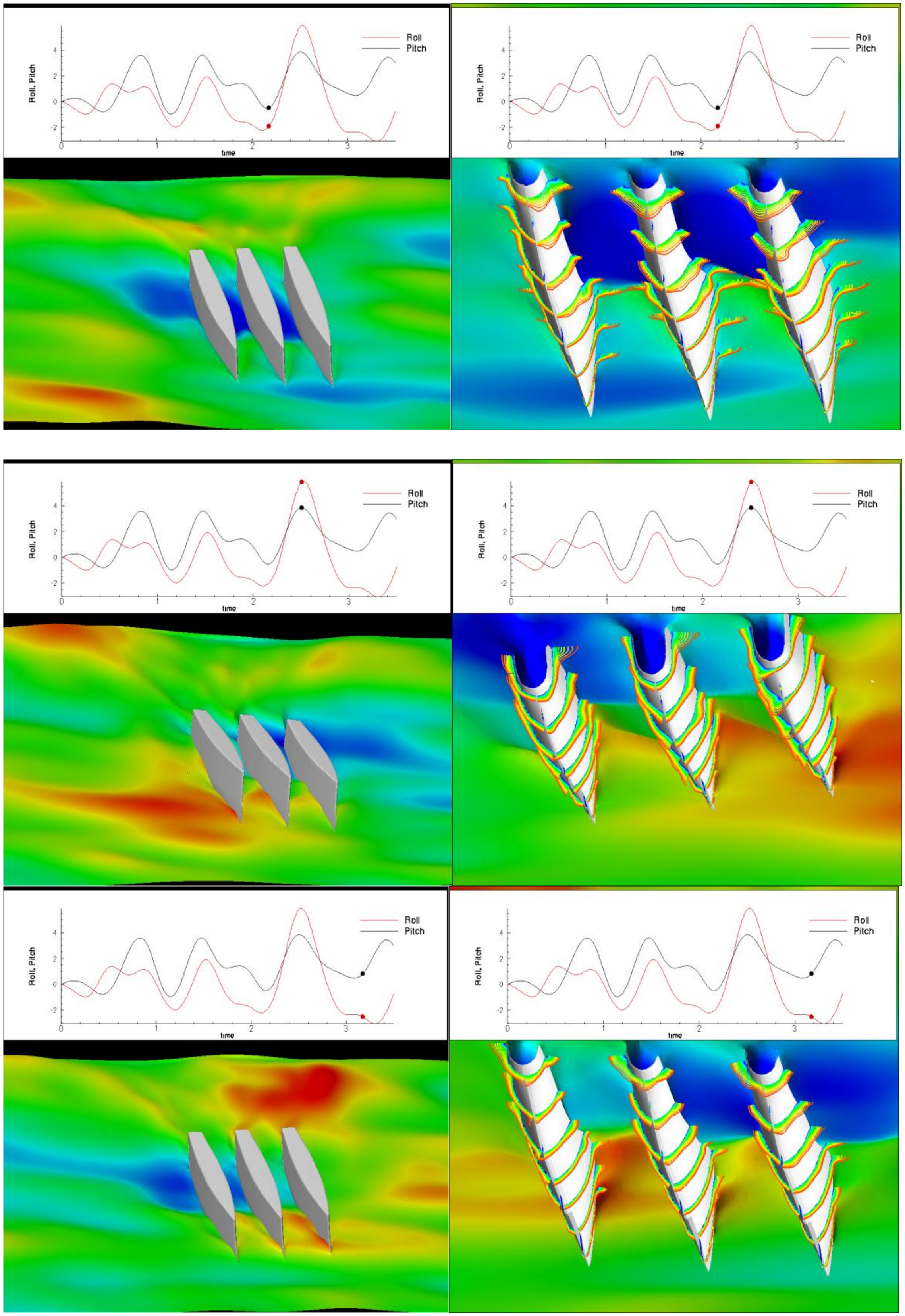


Fig 20 Free-surface and boundary layer for trimaran at 45^o heading from CFDShip

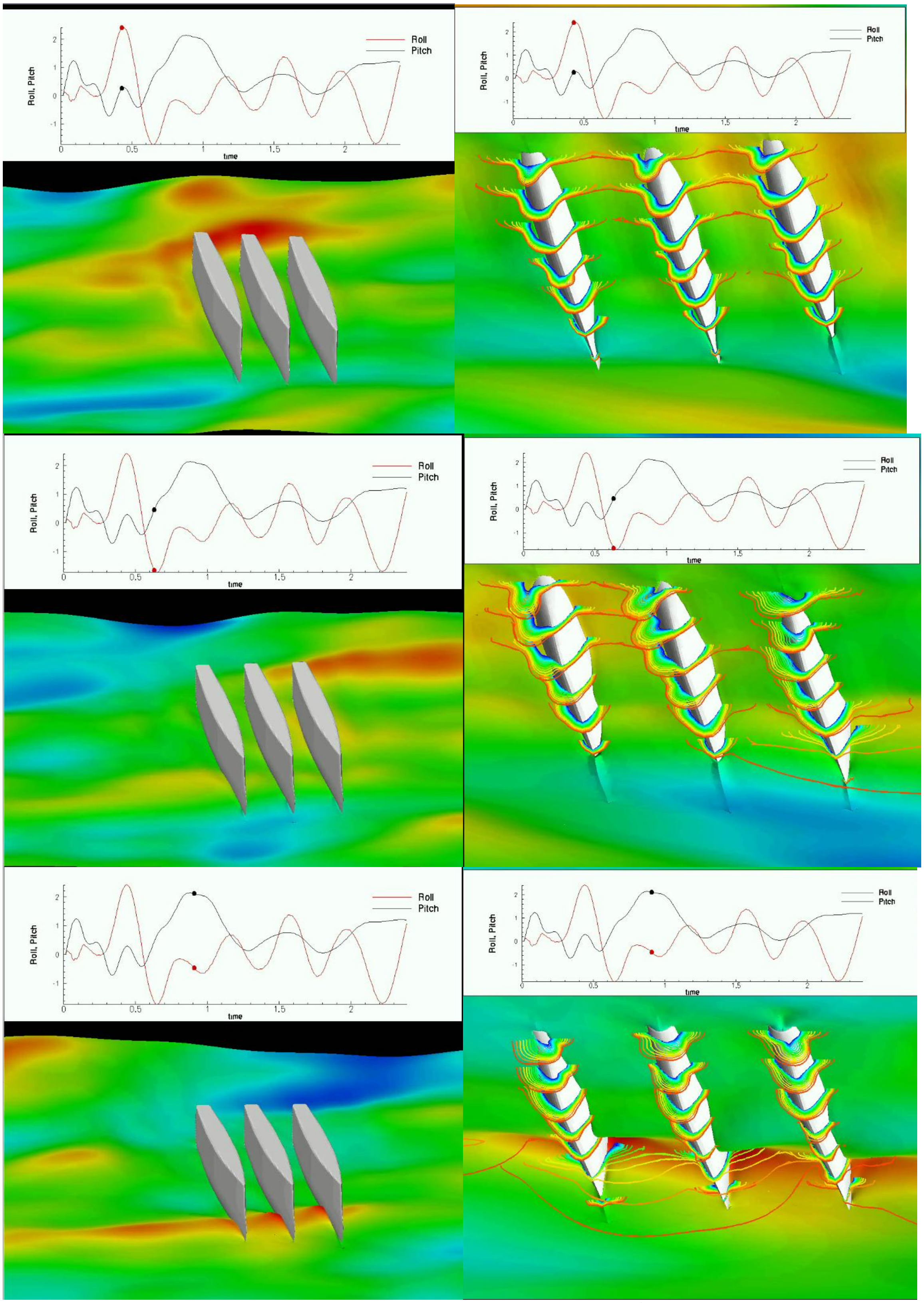


Fig 21 Free-surface and boundary layer for trimaran at 135° heading from CFDShip

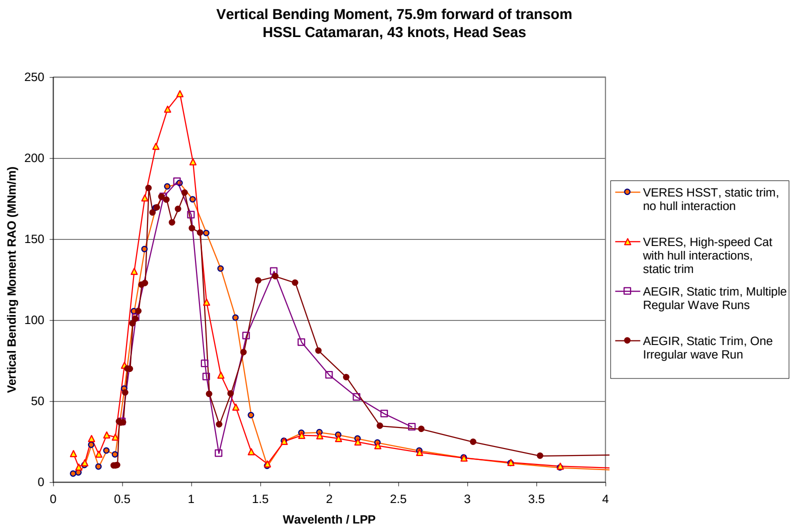


Fig. 22 Vertical bending moment RAO for HSSL catamaran at a position 75.9 meters forward of the transom in head seas at 43 knots

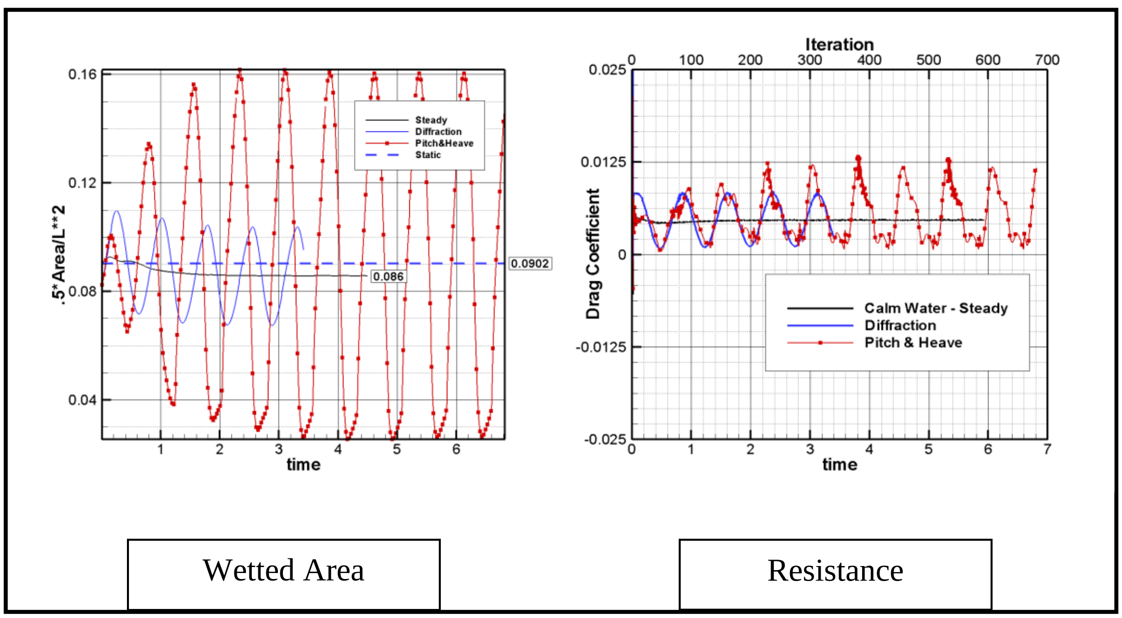


Fig. 23 Catamaran Wetted Area and Resistance vs. time (CFDShip)

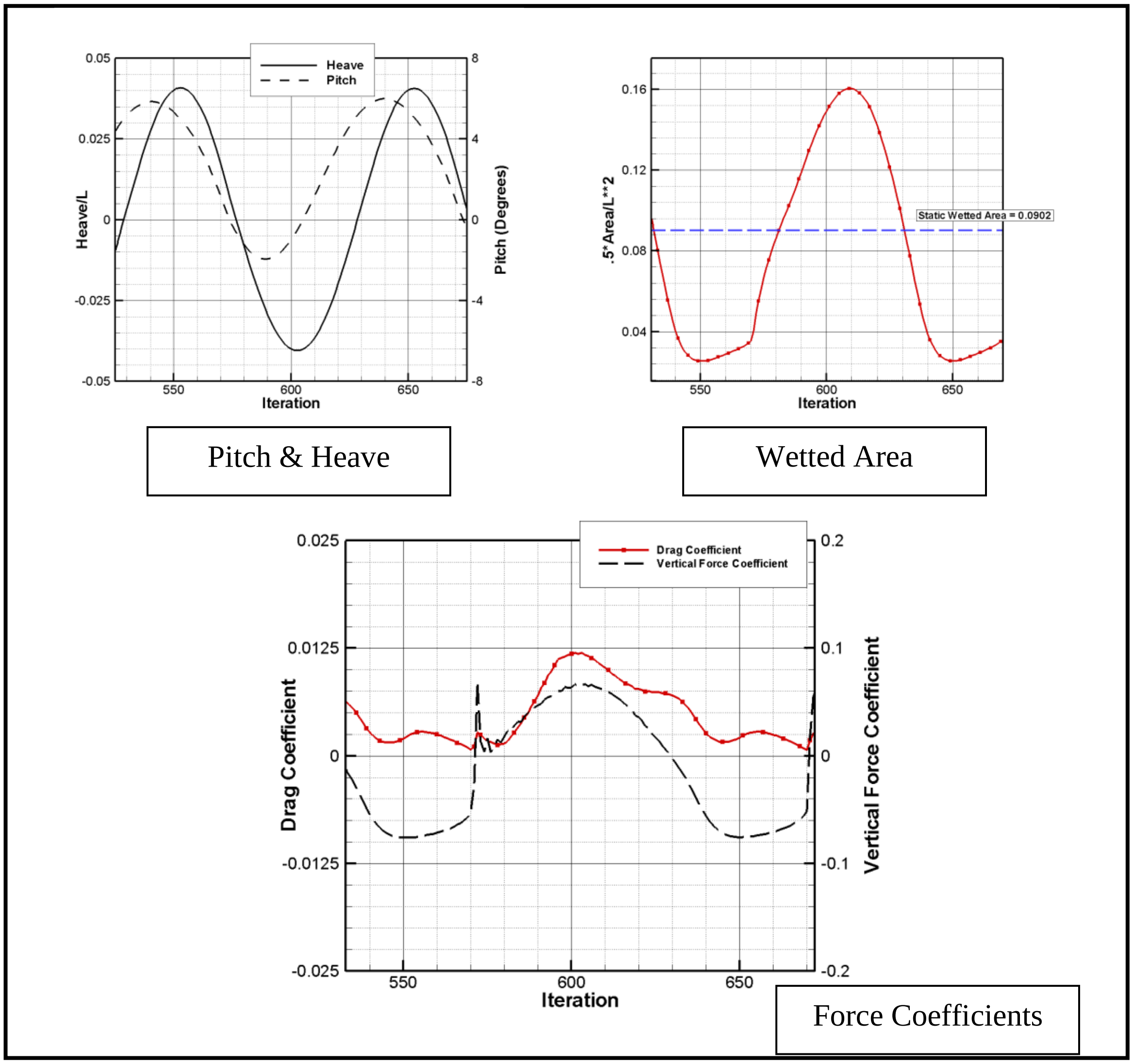


Fig. 24 Catamaran: Pitch & Heave Solution Detail (CFDShip)

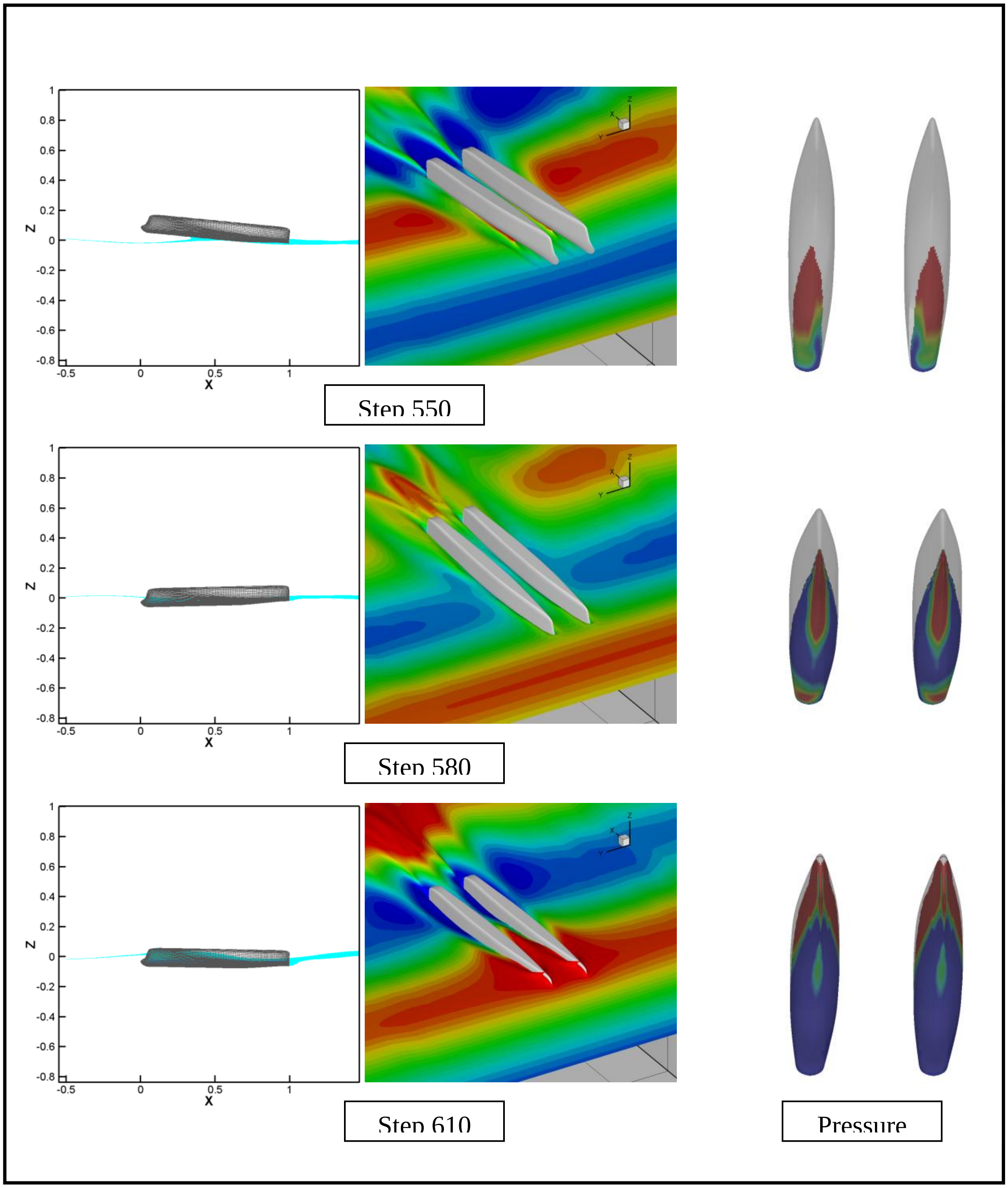


Fig. 25 Catamaran: Solution at steps 550, 580, and 610 (CFDShip)

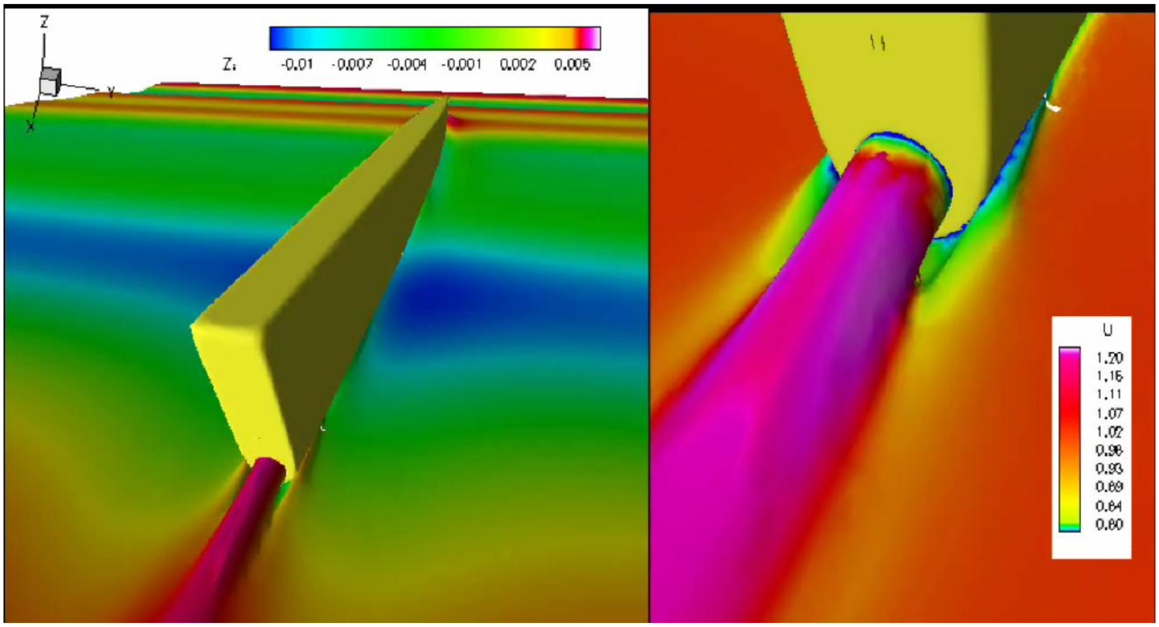


Fig 26 Demihull with water jet in irregular head seas (CFDShip)

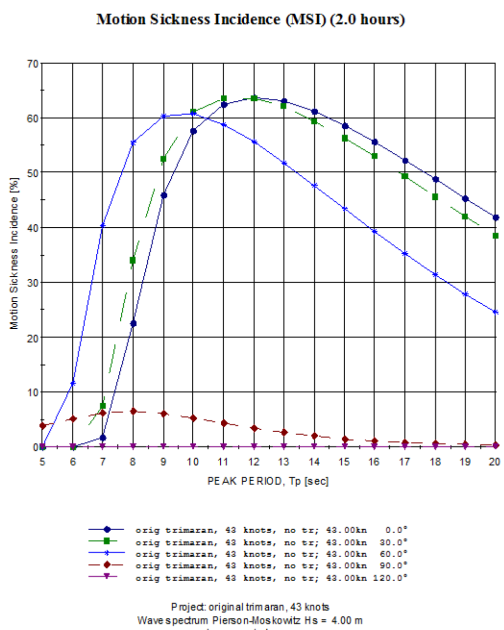


Fig. 27 VERES prediction for Motion Sickness Incidence (MSI) on the HSSL trimaran concept at 43 knots with various headings in a sea state defined with a Bretschneider spectrum with 4 meter significant wave height.

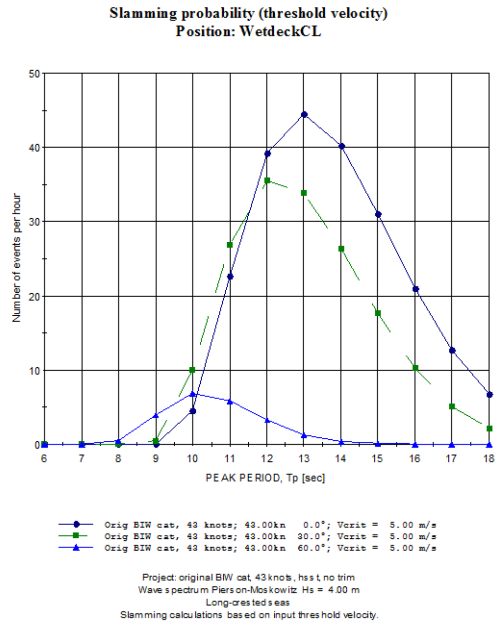


Fig. 28 VERES prediction for incidence of slamming on the centerline of the wetdeck of the HSSL catamaran concept at 43 knots with various headings in a sea state defined with a Bretschneider spectrum with 4 meter significant wave height.

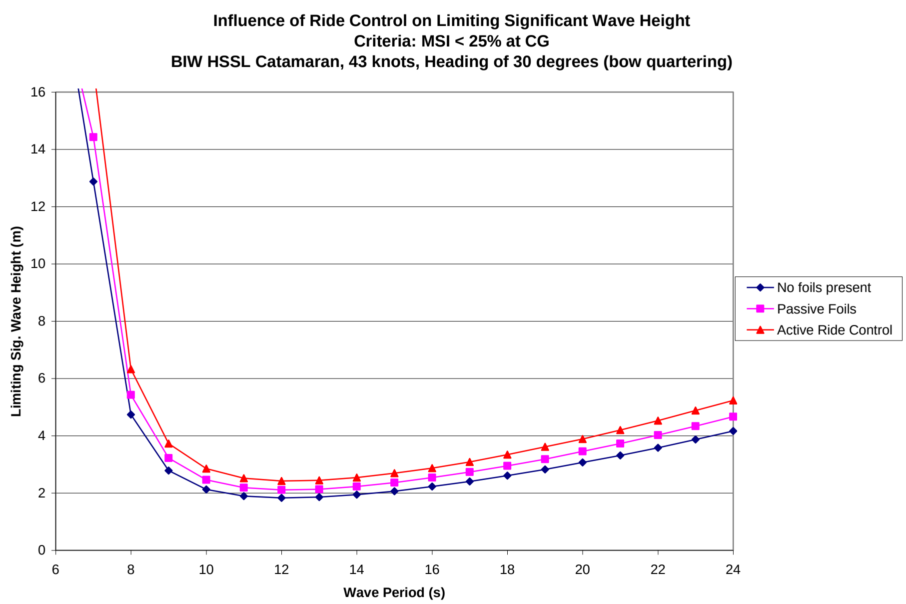


Fig. 29 Influence of passive and active ride control on limiting significant wave height to keep MSI below 25% on HSSL catamaran at 43 knots in bow quartering seas (VERES)

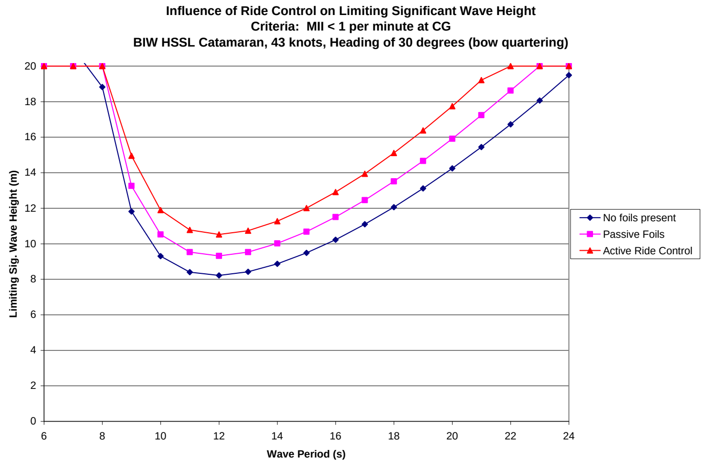


Fig. 30 Influence of passive and active ride control on limiting significant wave height to keep MII below 1 per minute on HSSL catamaran at 43 knots in bow quartering (VERES)

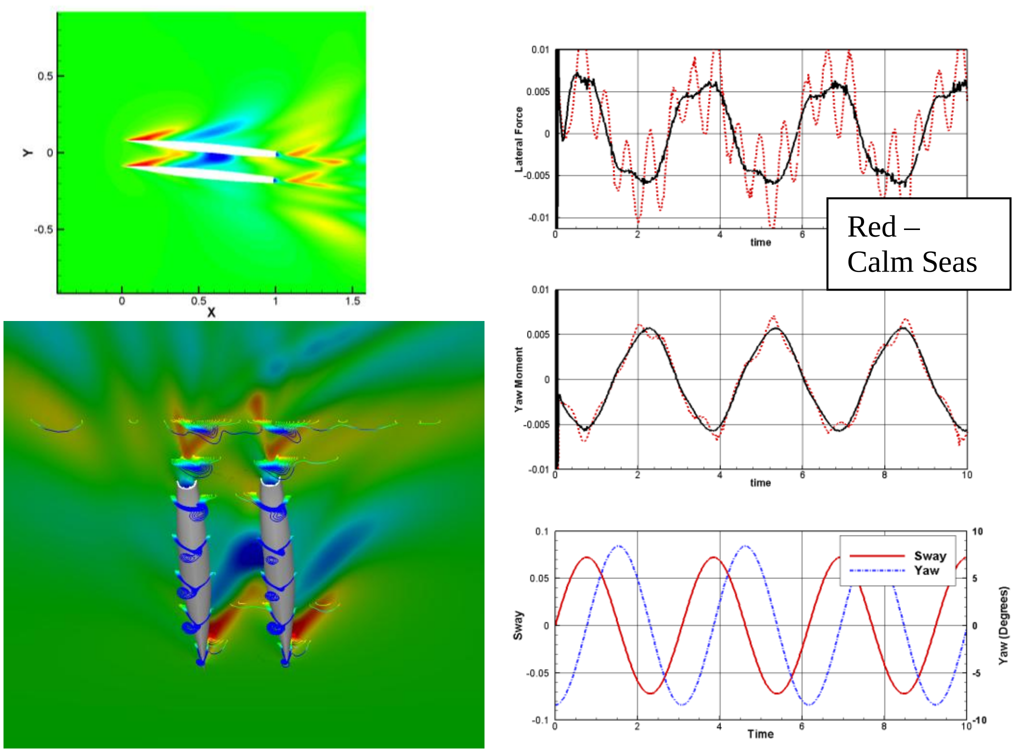
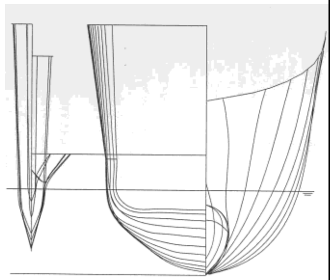


Fig. 31 HSSL Catamaran PMM Results (CFDShip)



C_P 0.71	LOA/B_X	17.18
C_B 0.53	B_X /T_X	2.23
C_{WP} 0.88	LCB to midships	4.56
C_B 0.74	LCF to midships	23.39
	LWL/ $\nabla^{1/3}$	10.55

	Trimaran	Centerhull/ Monohull
Total Ship		
Overall length (m)	323	323
Waterline length	313	313
Centerhull beam (m)	18.8	18.8
Total beam (m)	39.2	18.8
Draft at FP (m)	8.477	8.477
Draft at AP (m)	8.477	8.477
Total displacement (mt)	27,109	26,590
Total wetted surface area (sq m)	8,460	7,716
Transom immersion (m)	1.977	1.977
Transom area (sq m)	33.62	33.62
Centerhull depth (m)	22	
Cross-structure depth (m)	8.59	
Cross-structure clearance (m)	6.41	
VCG (m)	9.5	
LCG aft midships (m)	4.6	
Pitch gyradius/waterline length	0.27	
Roll gyradius/centerhull beam	0.48	
Sidehulls		
Length at design waterline (m)	51	
Beam (m)	3	
Draft (m)	6.5	
Displacement of two sidehulls (mt)	519	
Wetted surface area of two sidehulls (sq m)	745	

Fig 32 Model 5594

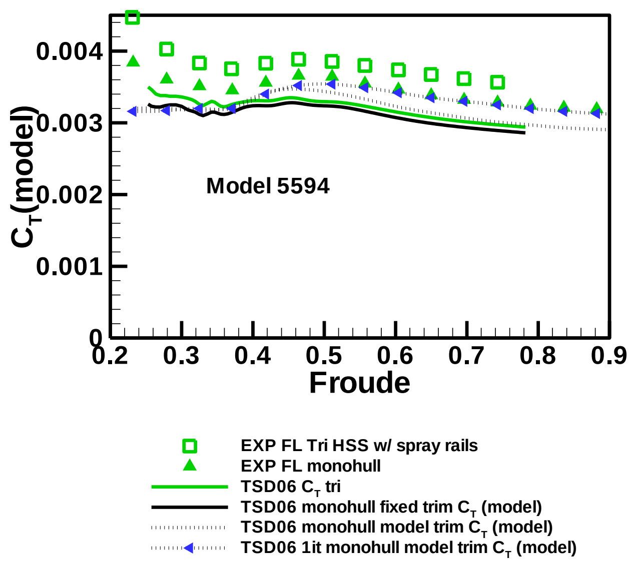


Fig. 33 TSD total resistance compared with model 5594.

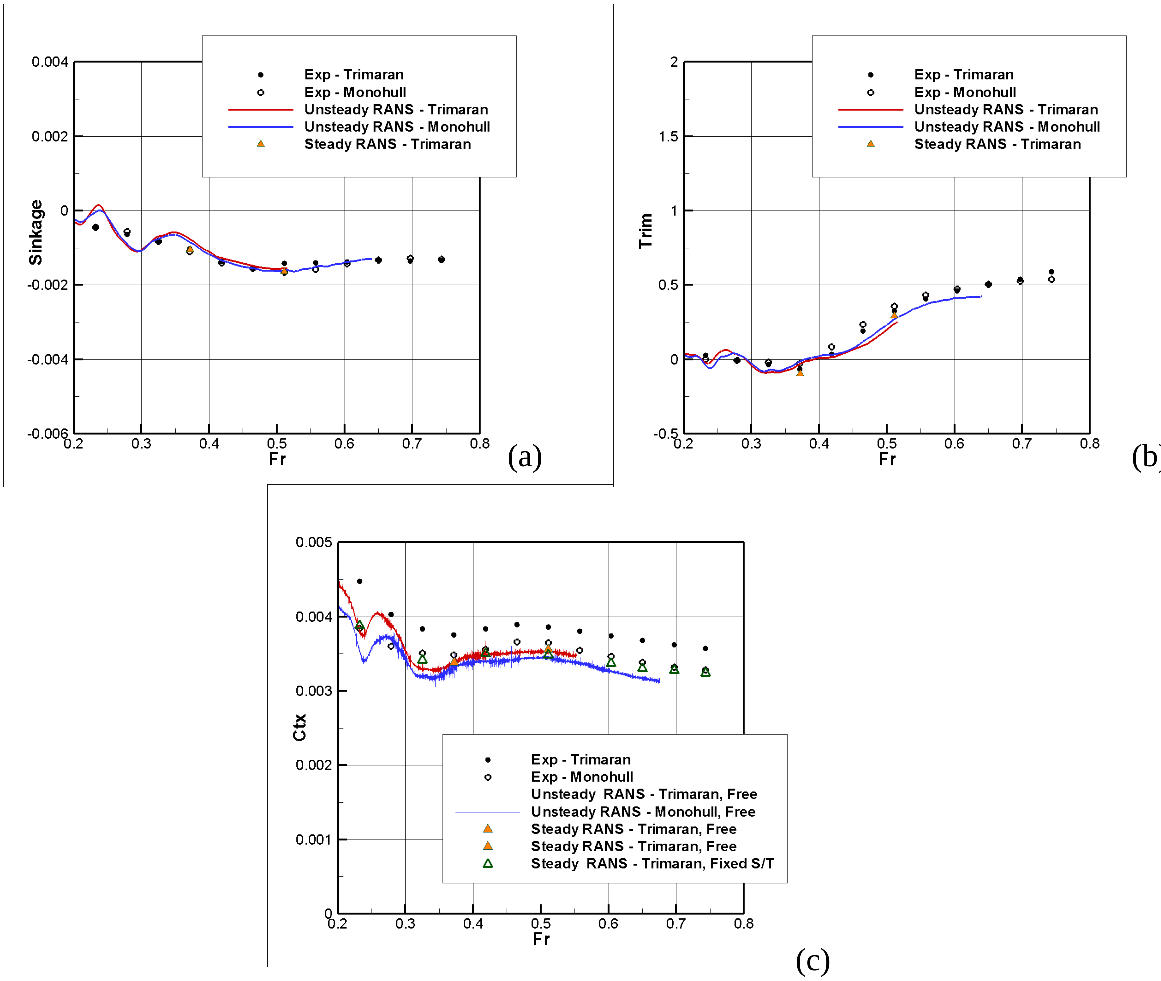


Fig. 34 CFDShip validation: a) Sinkage, b) trim, and c) C_T

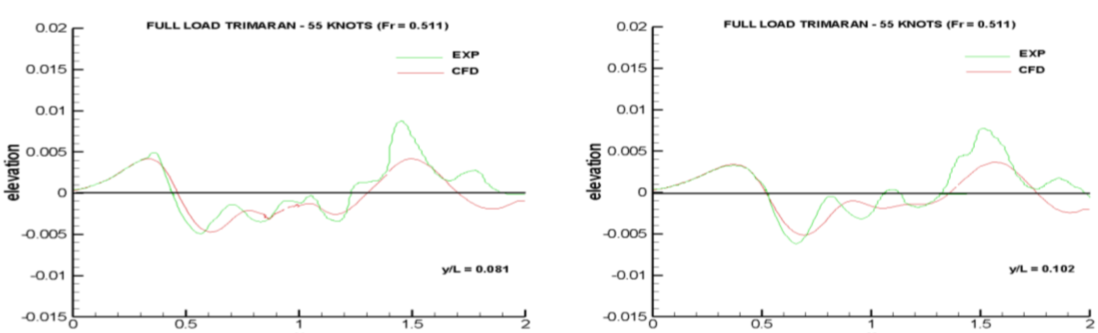


Fig. 35 Model 5594 Wave cuts comparison (coarse grid)

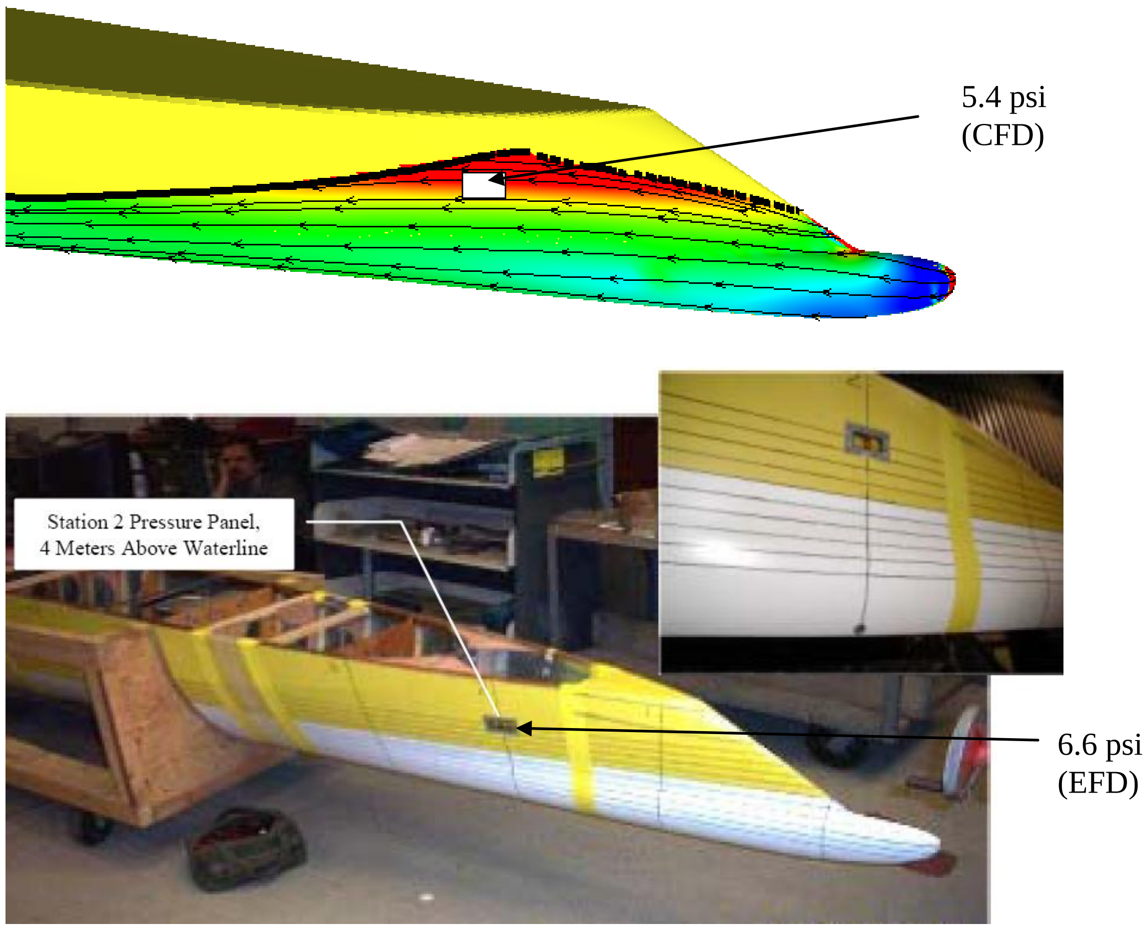


Fig. 36 Model 5594 Peak pressure comparison at 45 knots SS6