

CFD PREDICTION OF THE WAVE RESISTANCE OF A CATAMARAN WITH STAGGERED DEMIHULLS

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ABSTRACT

Although the catamaran configuration has been known for a long time, it is only in the recent past that such hull forms have enjoyed unprecedented usage in the high-speed ferry industry. One of the design challenges faced by naval architects is the accurate prediction of the hydrodynamic characteristics of such vessels, primarily in the areas of resistance, propulsion and seakeeping. Even though a considerable amount of research has been carried out in this area, there remains a degree of uncertainty in the prediction of calm-water resistance of catamaran hull forms. In our research, we examine the calm-water wave-resistance characteristics of a chine-hull-form transom-stern slender catamaran, based on computational fluid dynamics (CFD) modelling and thin-ship theory. We include here a validation and comparison of CFD predictions with experimental data. We also include the results of calculations by Hydros, a computer program developed at The University of New South Wales, which gives very accurate predictions of resistance of high-speed marine vessels. The hull forms comprise a conventional catamaran along with longitudinally staggered demihull configurations.

The investigation of a longitudinally staggered catamaran is to provide an unusual hull form for CFD analysis and to fill the knowledge gap between catamaran and trimaran wave resistance. Although considerable work has been done on the optimal position of trimaran outriggers for minimum resistance, significantly less work has been carried out on the centerline equivalent. While the hull form is not immediately practical, it is of great interest to understand the wave field interaction between the demihulls.

INTRODUCTION

Catamarans account for 43% of the fleet by vessel numbers as given by the report of Drewry Shipping Consultants (1997). Slender hull forms and higher speed capabilities provoked the need for technological evolution in predicting their preliminary characteristics of resistance. Calm-water resistance of catamarans is in general attributed to two major components, namely viscous resistance and calm-water wave resistance. The former has been acceptably determined from the ITTC 1957 line, using a frictional form factor. The latter still presents a stimulating question for the researchers. It is understood that the solution cannot be generalized by one simple formula but varied in accordance with specific configurations of catamarans.

With the advent of computational fluid dynamics (CFD), there is hope for further development. In this paper, a computational package, ShipFlow, is used to predict the wave-making resistance of a staggered catamaran hull form and the theoretical data has been compared against Hydros and experimental data. The work in this paper is concentrated on a hull possessing a single hard-chine with a transom stern.

NOMENCLATURE

B/T	Beam-draft ratio
C_A	Correlation resistance coefficient
C_B	Block coefficient
C_F	ITTC 1957 ship-model correlation line
C_M	Midship coefficient
C_P	Prismatic coefficient
C_R	Residuary-resistance coefficient
C_T	Total-resistance coefficient
C_W	Wave-resistance coefficient
F_n	Froude number
L/B	Length-beam ratio (demihull)
R_n	Reynolds number
R_T	Total resistance
S	Wetted-surface area
g	Acceleration due to gravity
r/L	Longitudinal stagger ratio (between demihull transoms)
s/L	Lateral separation ratio (between demihull centerplanes)
$1+k$	Form factor
ΔC_W	Wave resistance coefficient correction
ε_R	Residual drag-to-weight ratio
ϕ	Factor for pressure field change
ρ	Water density
σ	Velocity augmentation factor
γ	Viscous interference factor
τ	Wave-resistance interference factor
Δ	Displacement weight

ABBREVIATIONS

AMCSHC	Australian Maritime College Ship Hydrodynamic Centre
CFD	Computational Fluid Dynamics
ITTC	International Towing Tank Conference

KEYWORDS

Catamaran, Resistance, Wave Resistance, CFD

LITERATURE STUDY REVIEW

The paper by Doctors et al (1991) provides a glimpse of design constraints and resistance prediction of a high-speed river catamaran. A key feature of this analysis is the complex issue of addressing the restricted water depth and width of the river. Nevertheless, the theory appears to predict with reasonable accuracy the wave resistance of a river catamaran and good correlation exists between theoretical and experimental data.

The paper by Insel and Molland (1992) summarizes a calm-water-resistance investigation into high-speed semi-displacement catamarans, with symmetrical hull forms based on experimental work carried out at the University of Southampton. Two interference effects contributing to the total resistance effect were established; these are viscous interference, caused by asymmetric flow around the demihulls which affects the boundary layer formation, and wave interference, due to the interaction of the wave systems produced by each demihull. The authors proposed that the total resistance of a catamaran could be expressed by the equation:

$$C_{TCAT} = (1 + \phi k) \sigma C_F + \tau C_w \quad (1)$$

The factor ϕ has been introduced to take account of the pressure-field change around the demihulls and σ takes account of the velocity augmentation between the hulls and would be calculated from an integration of local frictional resistance over the wetted surface, while $(1 + k)$ is the form factor for the demihull in isolation. For practical purposes, ϕ and σ can be combined into a viscous interference factor γ where $(1 + \phi k) \sigma = (1 + \gamma k)$. Hence:

$$C_{TCAT} = (1 + \gamma k) C_F + \tau C_W \quad (2)$$

We note that for a demihull in isolation, $\gamma = 1$ and $\tau = 1$. For a catamaran, τ can be calculated from the equation:

$$\tau = \frac{C_{W\,CAT}}{C_{W\,DEMI}} = \frac{[C_T - (1 + \gamma k) C_F]_{CAT}}{[C_T - (1 + k) C_F]_{DEMI}} \quad (3)$$

The authors concluded that the form factor, for practical purposes, is independent of speed and should thus be kept constant over the speed range. This was a good practical solution to a complex engineering problem at that point in time. The authors further concluded that:

- The vessels tested have an appreciable viscous form effect, and this is higher for catamarans where viscous interference takes place between the hulls.
- Viscous resistance interference was found to be relatively independent of speed and hull separation, and rather is dependent on demihull-length-to-beam ratio.

In his investigation, Millward (1992) has reported his test results on a series of catamarans characterized by a hull-length-to-beam ratio L/B of 10 and a beam-to-draft ratio B/T of 2. Millward (1992) in fact intended to adhere to the common parameter range as suggested by Insel and Molland (1992). Figure 1, which is reproduced from this article, demonstrates the effect of separation ratio on resistance.

The following new wave-resistance coefficient was introduced:

$$C_W^* = \frac{R^*}{Fn^2} \quad (4)$$

in which, $R^* = \frac{R_W}{\frac{8}{\pi} \rho g \frac{B^2 T^2}{L}}$ and R_W is the wave resistance.

The frictional resistance was calculated using the ITTC 1957 line. From this, the total resistance R_T of the catamaran can be found by:

$$R_T = 2[(1 + k)R_F + R_W] \quad (5)$$

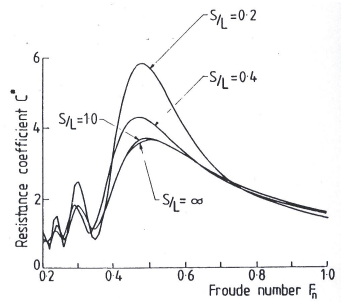


Figure 1: Effect of Hull Separation on Catamaran Resistance from Millward (1992)

The paper by Molland et al (1994) is an extension of the work conducted by Insel and Molland (1992). Additional models were tested with the particulars detailed in their report (1994). In addition to form factors derived from experimental data, Molland et al. (1994) gave the experimental data for a systematic series of high-speed displacement catamaran forms in which the viscous form factors have also been clarified. For further details on the resistance data readers are referred to the above report.

Zips (1995) proposed using a multiple-regression analysis of test data intended to predict the resistance of hard chine catamarans with hull parameters in the scope of the 1989 VWS Hard Chine Catamaran Hull Series.

The total resistance is given by:

$$R_T = R_F + \rho g \nabla \varepsilon_R \quad (6)$$

Hanhirova, Rintala and Karppinen (1995) have proposed a prediction method of estimating the resistance of high-speed mono- and multihull vessels based on Michell's integral along with a regression correction. The regression method is based on the resistance predicted by Michell's integral and model experiments carried out on 30 different hull shapes, several of which were catamarans and trimarans. A significant aspect of this method is that it can be applied to both mono- and multihull vessels in the preliminary design stage. It may be noted that the

regression coefficients for the correction to C_W have not been published. The regression correction was carried out as follows:

$$\begin{aligned} C_T &= C_F + C_R + C_A \\ C_F &= \frac{0.075}{(\log_{10} R_n - 2)^2} \\ C_A &= 0 \end{aligned} \quad (7)$$

The experimental residual coefficient was given by: $C_R = C_T - C_F$ which was used to calculate the required correction to the wave-resistance coefficient C_W as predicted by Michell's integral. The required correction to the wave resistance coefficient was given by:

$$\Delta C_W = C_R - C_W \quad (8)$$

Pham, Kantimahanthi and Sahoo (2001) conducted a rigorous CFD analysis of a systematic series of 18 hard-chine catamaran hull forms. The recorded data was then statistically analysed to determine an accurate regression equation. The established regression equation has been seen to deviate appreciably due to various sources of uncertainties. Verification of the equation with an experimental database is also lacking. The authors concluded that further research is therefore needed in order to refine the accuracy as well as to complete the selection of crucial parameters employed.

The research program undertaken by Schwetz and Sahoo (2002) was devised to:

- Examine variations in C_W using CFD, while modifying the basic hull parameters and maintaining the same displacement and LCB position.
- Examine variations in C_W using CFD, while modifying the basic hull parameters, including the displacement and LCB.
- Compare C_W results of CFD with results from towing-tank tests and develop a regression model.

The series of symmetrical hull shapes used in this study were generated by the authors, and are believed to closely represent the hull forms being used in industry at the moment. The models are not mathematical in nature, and do not form part of any published systematic series. Following a review of current vessel dimensions, a range of round-bilge, hard-chine and semi-SWATH vessels was generated. After an extensive CFD analysis, a reasonably accurate regression model was developed.

Sahoo, Browne and Salas (2004) have expanded on the work carried out by Schwetz and Sahoo (2002) by conducting further work on a systematic series of round-bilge catamaran hull forms and subjecting these to CFD analysis. The systematic series that was used for this analysis is based on typical hull forms used by the high-speed ferry industry in Australia. A parametric transformation procedure was used to produce the desired demihull series. The systematic series of demihulls thus produced was confined to an s/L ratio between 0.2 and 0.4 while the Froude-number range was constrained to between 0.2 and 1.0. A regression model was developed to predict the resistance of such round-bilge catamaran-hull forms.

Subramanian and Joy (2004) have illustrated a procedure for the rapid development of a hull form and preliminary prediction of resistance of high-speed catamarans with slender demihulls. They have made use of Michell's integral for slender vessels to estimate the wave resistance of demihulls, which combined with the average form factor value of 1.42 and the ITTC 1957 friction line would provide the total resistance.

Although considerable work has been carried out by various authors since 1991 on catamaran resistance prediction, little work has been carried out regarding the staggered demihull configuration, other than the investigation undertaken by Soeding (1997). Soeding (1997) defined a staggered catamaran hull form, called a Weinblum, after the celebrated hydrodynamicist Georg Weinblum. In the paper, Soeding (1997) confirmed from theoretical and experimental investigations that the resistance of a catamaran, with a staggered demihull configuration, could have as much as 50% less resistance than a non-staggered catamaran. In fact, it was further stated that the seakeeping characteristics were even better when compared with those of a conventional catamaran hull form. The transverse wave system contributes significantly to the resistance and these add up constructively because of the similar wave pattern and phase generated by both demihulls. Since energy in a wave is proportional to the square of the wave amplitude, it would imply that, with a simple catamaran configuration, there would be a fourfold increase in wave energy and consequently a fourfold increase in wave resistance over a single hull. However, as Soeding (1997) suggested, if one were to introduce a phase shift of 180 degrees by way of a longitudinal shift of a demihull, a considerable decrease in resistance could be achieved. Some of the major conclusions of this paper were:

- Longitudinal shift is the most important parameter for resistance reduction.

- Total resistance and propulsion power reduction of almost 50% for a longitudinal shift of $0.5L$ over a range of F_n values of 0.40 to 0.65.
- Asymmetry improves the seakeeping characteristics and has no appreciable effect on manoeuvrability of the vessel.
- For a Weinblum model, the vertical bending moment could be roughly twice that of a conventional catamaran but other wave loads and still-water bending moment are smaller.

In light of the above literature survey, it was decided to undertake a CFD simulation and some experimental work on a catamaran vessel. CFD simulations were carried out by use of ShipFlow and Hydros to replicate the experimental work conducted in the AMCSHC so that a comparative analysis could be undertaken.

SHIPFLOW AND HYDROS

ShipFlow has been found to be applicable to the calculation of ship-hull resistance (both viscous and wave components), development of the wave profiles and consequential matters, such as trim and sinkage characteristics, and the changes in velocities and pressure field around appendages, such as the propellers. Some of these problems remain a challenge to researchers in order to produce a sufficiently reliable CFD program to handle the complex phenomenon of fluid and object interactions.

The development of ShipFlow (2003) is based on three major methods - each applied in its most efficient zone with respect to the ship:

- Zone 1: Potential-flow method.
- Zone 2: Boundary -layer method.
- Zone 3: Navier-Stokes method.

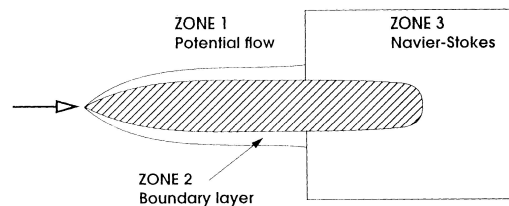


Figure 2: Zonal Distribution for Fluid-Flow Computation in ShipFlow

The laminar flow starts from the stagnation point, diverges gradually as it moves downstream, and when it reaches the transition point where the viscous force is insufficiently strong to bond the streamlines, it breaks down and become turbulent.

The potential-flow method is used to analyze the fluid flow in the outermost area of the region, designated as Zone 1 in Figure 2. In this zone, the fluid flow is treated as continuous streamlines starting from the forward end of the ship, and extending back to the aft end. The region that includes the thin boundary layers along the ship hull is referred to as Zone 2. The nature of fluid-flow change as the fluid moves along the hull in this region. Boundary layer theory is used to compute the fluid characteristics in Zone 2. The remaining region is fully turbulent and includes the wake. It is specified as Zone 3 and extends far aft from the transition point, which is usually about amidships. The Navier-Stokes theory is applied in this zone.

The assumptions that the fluid is incompressible and Newtonian allow for simplification of the fundamental equations for hydrodynamic applications. So the continuity equation and the subsequent conservation-of-momentum equations are all that are required in order to solve for the velocity and pressure fields of an incompressible flow. Thus, Hydros is based on the thin-ship approach. The reader is referred to the work of Doctors (2003), where the method is detailed. This essentially inviscid analysis can be easily modified in order to account approximately for all the effects of viscosity, surface tension, and surface elasticity (representing surface contaminants).

MODEL AND TOWING-TANK PARAMETERS

A series of model tests was conducted at the Australian Maritime College Hydrodynamic Centre (AMCHC). Several different tests were conducted over a set of three different conditions. All testing was conducted with the same transverse hull spacing. The conditions are outlined in Table 1. The catamaran that was tested comprised a single-chine hull form as shown in Figure 3 below. The details of the parameters are provided in Table 2.

Table 1: Test Conditions for Catamaran Model

Condition	Longitudinal Stagger r/L	Transverse Spacing s/L	Water Depth (m)
1	0.00	0.3	1.50
2	0.25	0.3	1.50
3	0.50	0.3	1.50

Table 2: Parameter Details of Model Demihull

Displacement Δ	15.244 kg
Draft T	0.06936 m
Length at WL L_{WL}	1.694 m
Beam at waterline B	0.1899 m
Block coefficient C_B	0.6844
Prismatic coefficient C_p	0.7292
Wetted-surface area S	0.4171 m ²



Figure 3: Catamaran model in the Staggered Configuration

The AMCHC towing tank has a length of 100 m and a width of 3.55 m. The water depth was maintained at a constant depth of 1.5 m. The towing tank also has the possibility for accurate testing in very shallow water depths.

RESULTS

Both ShipFlow (CFD) and Hydros computations were carried out to replicate the towing-tank conditions. That is, the depth and width were properly taken into account. The total resistance calculations, in the case of ShipFlow, were undertaken through the following steps:

- Wave-resistance coefficient C_w determined from the ShipFlow computation, which takes into account the wave interference effects, thus effectively calculating τC_w .
- Viscous-resistance coefficient was calculated using the ITTC 1957 ship-model correlation line.
- Total-resistance coefficient was then calculated using $C_{TCAT} = (1 + \phi k) \sigma C_F + \tau C_w$

- In the present case, it may be noted that $\sigma = 2$ for two demihulls and $k = 0$, since there is no adequate information available for viscous interference effects.
- Finally, the data was plotted in the form of total-resistance-to-weight ratio (that is, the specific resistance) over the relevant Froude-number range.

Figures 4, 5 and 6 depict the comparative analysis of ShipFlow and Hydros data against the experimental data. Figure 7 represents the experimental values for the three different stagger cases.

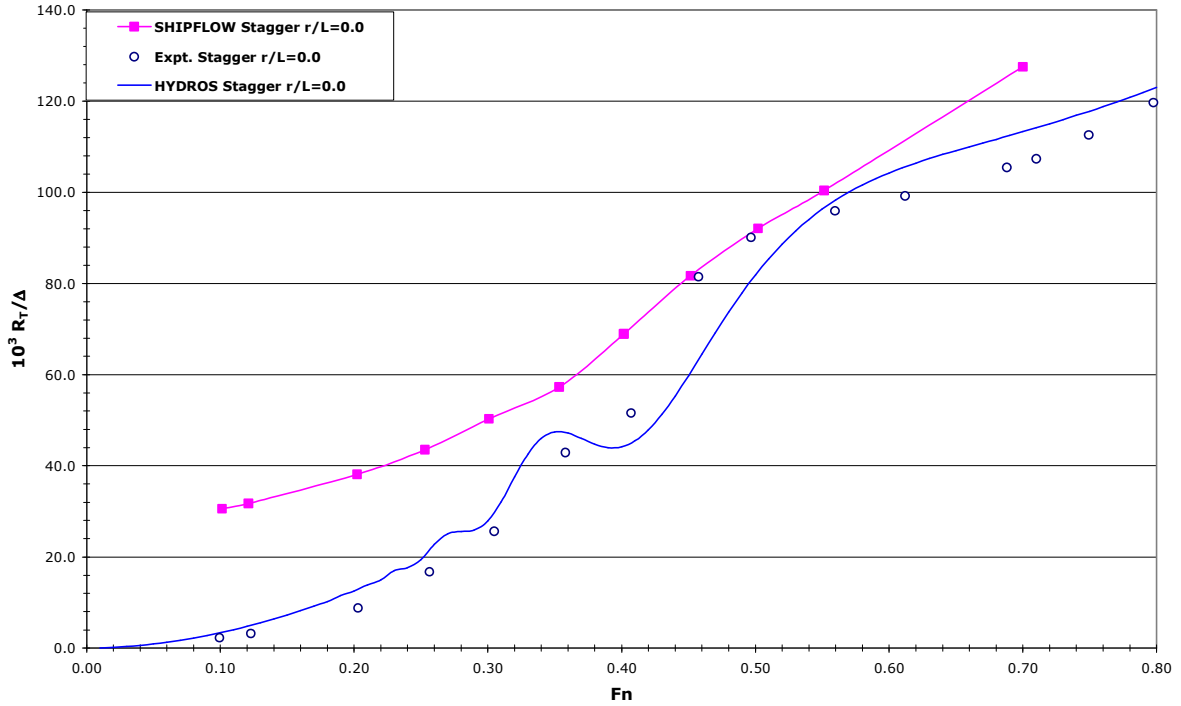


Figure 4: Comparison between Experimental and Theoretical Predictions for the Stagger: $r/L=0.0$

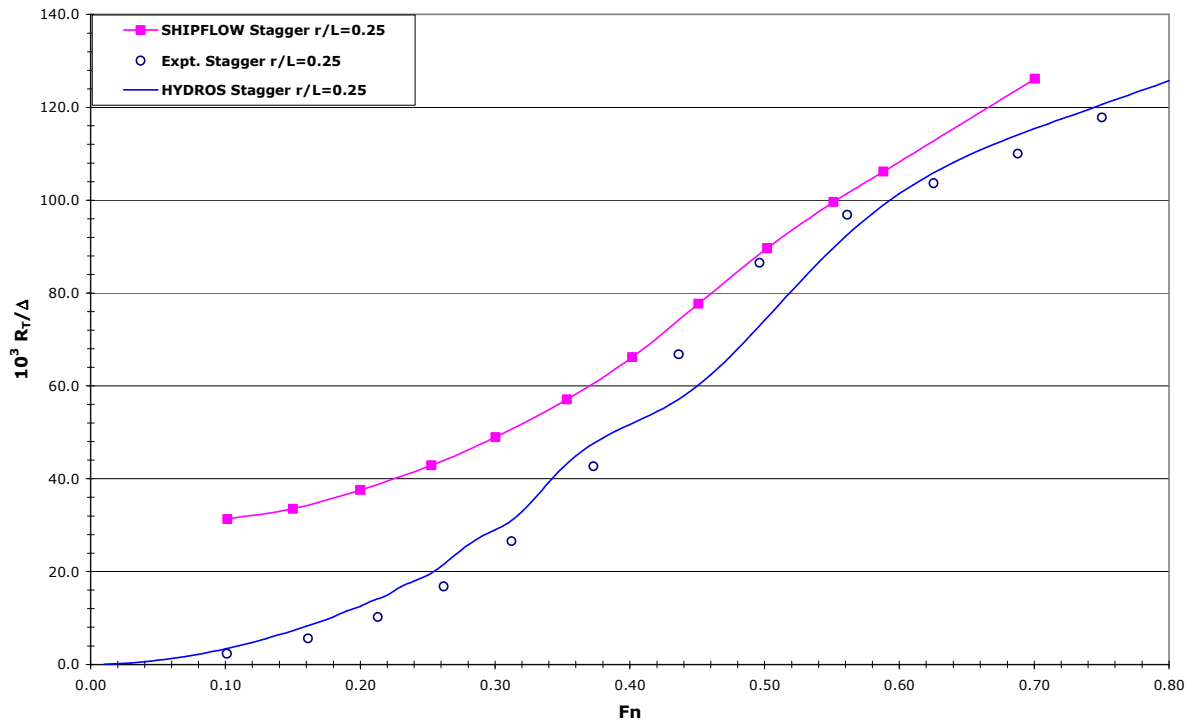


Figure 5: Comparison between Experimental and Theoretical Predictions for the Stagger: $r/L=0.25$

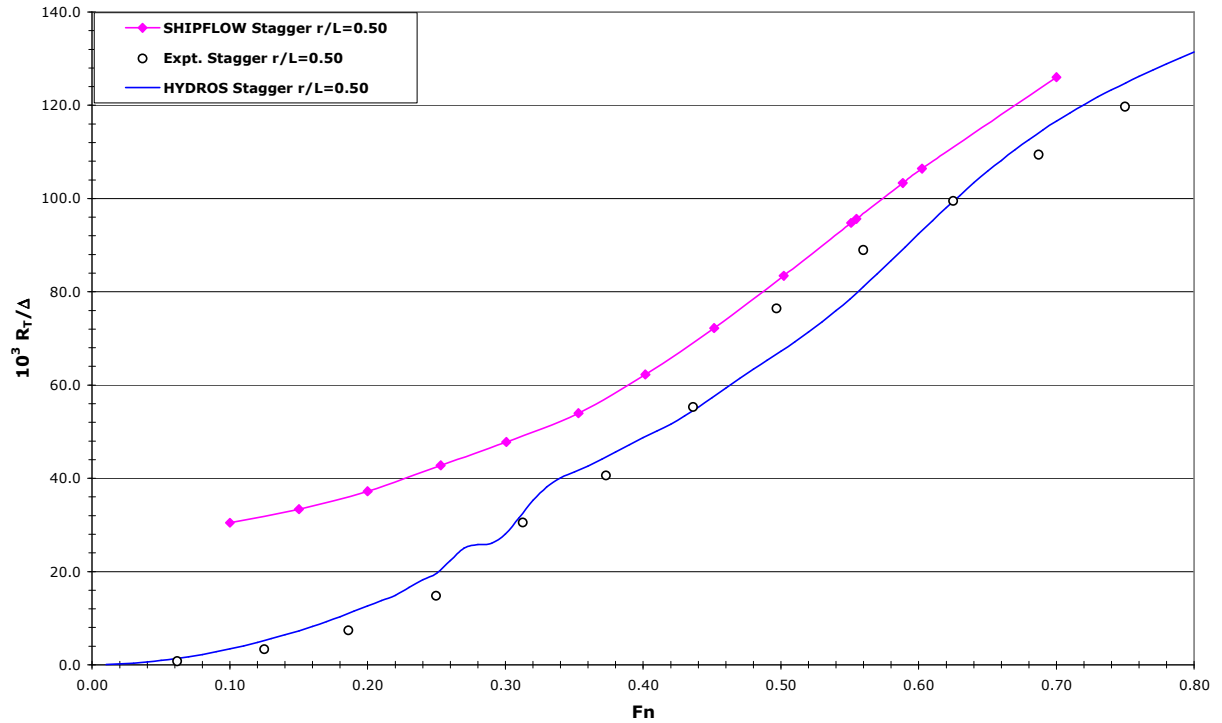


Figure 6: Comparison between Experimental and Theoretical Predictions for the Stagger: $r/L=0.50$

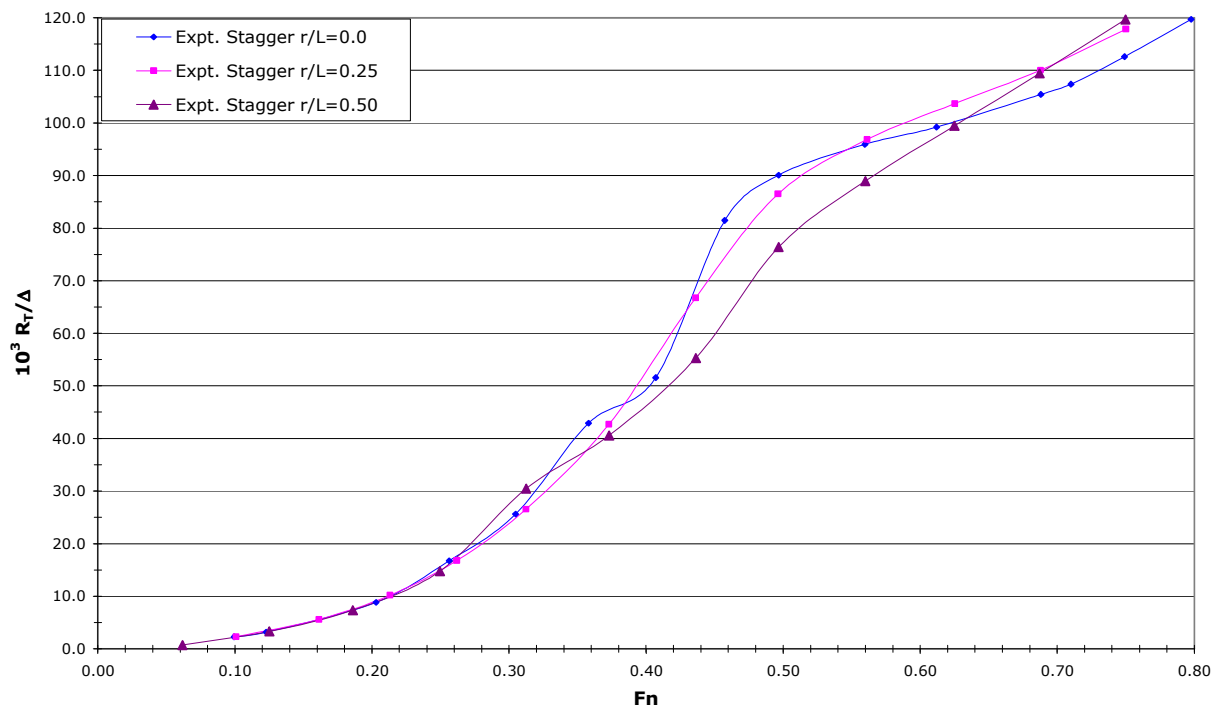


Figure 7: Experimental Resistance-to-Displacement-Weight Ratio for all Stagger Cases

CONCLUSIONS AND DISCUSSIONS

From the figures depicted above, it is apparent that the experimental results correlate very closely well with the numerical predictions of Hydros. ShipFlow only exhibits good correlation with the experimental results in a small domain, namely between Fn values of 0.45 and 0.60. Outside this range, there appears to be a large overprediction

by ShipFlow. It is thought that this large discrepancy is due to the very large transom stern that the model possesses and the fact that this program does not attempt to model the partially ventilated conditions that would occur over the major part of the speed range covered by this investigation. It may be noted that the total-resistance computation in ShipFlow has a component related to viscous resistance, which uses the ITTC 1957 friction line, and which has not incorporated any viscous resistance interference factor ϕ as shown in Equation 1.

The following conclusions can be drawn based on these limited experimental and numerical computations:

- Implementation of a suitable viscous interference factor is probably important for ShipFlow.
- Since the general trend is similar to the experimental values, ShipFlow could be used in the initial design stages as an optimisation tool where systematic variation of parameters is to be performed.
- Hydros displays extremely good correlation for all three stagger cases and over the entire Froude number range.
- Further experimental work needs to be carried out over a wide range of hull forms to ascertain the effectiveness of resistance reduction due to the staggering of the demihulls.
- It is evident that a significant reduction in resistance could be achieved by finding the optimum position of the stagger, which confirms the conclusions arrived at by Soeding (1997).
- Experimental data, as plotted in Figure 7, clearly emphasizes that, below Fn values of 0.35, no significant gains could be achieved. Between Fn values of 0.35 and 0.7, the range in which a vessel is most likely to operate, it appears that favorable (that is, destructive) interference does take place in the wave system and the vessel with maximum stagger shows a considerable reduction in resistance. Above Fn values of 0.7, no conclusion can be drawn with such limited experimental data.

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