Wave Resistance Prediction of Hard-Chine Catamarans through Regression Analysis

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Abstract

This paper establishes a regression equation to estimate the wave resistance of a systematic series of high-speed, hard-chine catamarans based on the data attained by using SHIPFLOW, a CFD software package. The primary aim of this investigation is to determine wave resistance characteristics of slender hard-chine configurations of catamaran hull forms in the high-speed range corresponding to Froude numbers up to 1.5. A systematic series of 18 hard-chine demi-hulls were generated, and their wave resistance in calm water determined using SHIPFLOW. Nature and degree of reliability of SHIPFLOW software package have been briefly examined. Relevant technical papers have been reviewed and the significant variables identified for the regression equation. The recorded data were then statistically analysed to determine an accurate regression equation. The achieved regression equation has been compared with three empirical methods that have commonly been used so far.

The accuracy of the established regression equation has been seen to deviate appreciably by various sources of uncertainties. Verification of the equation with experimental database is also lacking. Further research is therefore needed to refine the accuracy as well as to complete the selection of crucial parameters employed. However, the results obtained have shown considerable promise, and a regression equation for predicting wave resistance of catamarans in calm water can be seen as achievable.

1. 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 of technological evolution in predicting their preliminary characteristics of resistance. Calm water resistance of catamarans is in general attributed to two major components namely, frictional resistance and calm water wave resistance. The former has been acceptably determined from ITTC-1957 line whilst the latter still remains to be a stimulating question to the researchers. It is understood that the solutions cannot be generalised 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 generate data of wave making resistance of hard chine hull forms, and the regression equations were developed based on the data. In the end credibility of these equations have been compared with several other theoretical methods presently available. The present length of catamarans is limited to 120-130 m and this paper concentrates on single hard-chine hull forms with transom stern. The model parameters have been based on data of modern catamarans found from the literature survey and on the suggestions given by Doctors et al. (1996).

2. Prediction Of Total Resistance - Background

The background of the work has been based on some of the important modern methods in application so far. These methods have been briefly explained below.

a) Insel & Molland's method (1991)

This method was developed based on linearised wave resistance theory and experimentally compared with test data from a Wigley hull form and a series of three round bilge hull forms at different values of separation ratios. This method is applicable to catamarans possessing parameter ranges as shown in table 1. The total resistance of the catamarans is given by:

$$C_{Tcat} = (1 + \phi k)\sigma C_F + \tau C_W \qquad (1)$$

Where, ϕ is introduced to take account of pressure field change around the demi-hull 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 and $(1+k)$ is the form factor for the demi-hull in isolation. For practical purposes, ϕ and σ can be combined into a viscous interference factor β, where

$$(1 + \phi k)\sigma = (1 + \beta k) \qquad (2)$$
$$C_{Tcat} = (1 + \beta k) C_F + \tau C_W \qquad (3)$$

Where τ is wave resistance interference factor and is given by:

$$\tau = \frac{C_{W_{cat}}}{C_{W_{mono}}} = \frac{[C_t - (1 + \beta k)C_F]_{cat}}{[C_t - (1 + k)C_F]_{mono}} \qquad (4)$$

For demihull in isolation, $\beta = 1$, $\tau = 1$.

In addition to this report of Molland et al. (1994) gives the experimental data of a systematic series of high-speed displacement catamaran forms in which the viscous form factors are shown as in table 2.

b) VWS Hard Chine '89 Series Regression Methodology (1995)

This method was proposed by Zips (1995) using multiple regression analysis of test data intended to predict the resistance of hard chine catamarans with hull parameters in the scope of the VWS Hard Chine Catamaran Hull Series '89. This series is valid for the ranges shown in table 3.
The total resistance is given by:

$$R_T = [R_F + (\varepsilon_R \times \nabla \times \rho \times g)] \qquad (5)$$

Where, R_F, the frictional resistance and the residual drag-to-weight ratio, ε_R are given by Zips (1995).

c) Millward's Method (1992)

In his investigation Millward (1992) has reported his test results on a series of catamarans characterised by hull length-to-beam ratio (L/B) of 10 and a beam-to-draft ratio (B/T) of 2. Millward (1991) in fact intended to adhere to the common parameter range as suggested by Insel and Molland (1991).
He introduced a new wave resistance coefficient ,

$$C_W^* = \frac{R^*}{Fn^2} \qquad (6)$$

where, $R^* = \dfrac{R_W}{\dfrac{8}{2} \rho g \dfrac{B^2 T^2}{L}}$ and R_W is the wave resistance.

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

$$R_T = 2[(1 + k)R_F + R_W] \qquad (7)$$

3.   Series Generation

The result of the literature survey on 50 contemporary catamaran configurations when integrated with the results shown by Doctor's et al. (1994) have led to the parameters shown in table 4. A parent hull form was developed with $C_B = 0.55$, L/B=15 and B/T=2.0. Basing on this hull form, a total of 18 models were developed (total including the parent hull form). The details of the models are shown in the table 5. Only the demi-hulls were considered during hull form generation which were later

extended to twin hulls, with demi-hulls being symmetrical with respect to each other and with respect to their individual centre-line planes.

4.   Computational Fluid Dynamics program – SHIPFLOW

SHIPFLOW was developed as a pioneering effort to address the complication of fluid flow characteristics around moving objects both in fully submerged situation and in free surface situation. Even though SHIPFLOW is intended specially for marine applications, it has also been extended to sufficiently solve closely related problems such as highly turbulent flow around automobiles.

Major areas in which SHIPFLOW has been found to be highly applicable include calculation of ship hull resistance both viscous and wave-related, development of wave profiles and sequential matters consisting of trim and sinkage characteristics, changes in velocities and pressure field around objects such as propellers. Some of these problems remain a challenge to researchers in order to produce more sophisticated CFD program to handle the complex phenomenon of fluid and object interactions.

According to Larsson (1993), the development of SHIPFLOW is based on three major methods each applied in its most efficient zone of fluid condition:
(i)   Zone1: *Potential flow* method.
(ii)   Zone2: *Boundary layer* method.
(iii)   Zone3: *Navier-Stokes* method.

Potential flow method is used to analyze the fluid-flow in the outermost area of the free surface designated as Zone 1 in Figure 4. In this zone the fluid-flow is treated as continuous streamlines starting from fore end of the ship, and extending up to the aft end. The region of free surface that describes the thin boundary layers along the ship hull is defined as Zone 2. The nature of fluid-flow change as the fluid moves along the hull in this region. The *boundary layer* theory is used to compute the fluid characteristics in zone 2. The laminar flow starts from the stagnation point, diverge gradually as it moves downstream, and when they reach the transition point where the viscous force is insufficiently strong to bond the streamlines, it breaks down and become turbulent.

The remaining region of the free surface is fully turbulent and will have wakes. It is specified as zone 3 and extending far aft from the transition point which is usually about amidships. *Navier- Stokes* theory is applied in this zone to calculate the energy and hence the corresponding resistance incurred.

5.   Outputs of SHIPFLOW

SHIPFLOW takes the offset table of half a demi-hull as the input data. Even though SHIPFLOW is capable of computing both frictional and wave resistance coefficients, only the latter is analysed since the purpose of this paper is to predict the wave-making resistance and the frictional resistance coefficient can be adequately estimated using ITTC-1957 line. Figures 4 to 7 illustrate wave profiles for model M17 at Froude number of 1.0 and different hull separation-to length ratios.

6.   Regression Analysis of C_w Data

(a) Independent variables

In conducting the regression analysis of the data, it is worthy to know the dependent and independent variables. In ascertaining the independent variables, this paper followed the guidelines given by Fairlie (1975). Fung (1993) has proposed the advantages and disadvantages of the speed dependent against speed independent regression analysis. The later has been utilized to develop the mathematical models.

(b) Selection of variables

A speed independent regression model has been chosen to develop the regression equations for Froude numbers from 0.4 to 1.5 in increments of 0.1. The computation of frictional resistance coefficients (C_F) complies with the ITTC 1957 line. The choice of C_W as the dependent variable was determined instead of total resistance coefficient since it is very ambitious to assign a form factor for an individual model without tank tests. Furthermore, other literature studies have also used C_W–Fn to illustrate the results from speed-independent regression analysis.

Clarke (1975) proposed a regression equation format for resistance coefficient in which block coefficient C_B has been used as a useful independent variable. According to Clarke (1975), when we look at the variables that effect wave resistance, the initial selection needs to be more general and may look like this:

$$C_W = f\{ L, B, T, LCG, C_B, C_P, C_M, L/B, B/T, L/\nabla^{1/3}, S/L, Fn \} \qquad (8)$$

Carmock (1999) reduced the number of variables to be evaluated basing on the following arguments:
- Length, beam and draught are covered by the ratio functions and therefore can justifiably removed due to duplication.
- $C_B = C_P \times C_M = \dfrac{\nabla}{LBT}$ and therefore it can be argued that C_B would cover variations in $L/\nabla^{1/3}$, C_P, and C_M. Hence, $L/\nabla^{1/3}$, C_P, and C_M can be discounted.

Hence wave resistance coefficient can be represented as shown in equation 9.

$$C_W = f\{ L/B, B/T, C_B, S/L, Fn \} \qquad (9)$$

As this analysis is speed-independent, Fn can be discounted. Therefore the final selection of four independent variables S/L, B/T, L/B and C_B results to:

$$C_W = f(L/B, B/T, C_B, S/L) \qquad (10)$$

(c) Generalised Form of Regression Equation

With C_W as the dependent variable, and the target vessel type being catamaran where S/L could be a significant parameter, the following expression has been assumed for wave resistance coefficient:

$$C_W = Const.(L/B)^{\beta_1} (B/T)^{\beta_2} C_B^{\beta_3} (S/L)^{\beta_4} \qquad (11)$$

By taking natural logarithms of both sides, the above expression can be written as:

$$ln(C_W) = \alpha + \beta_1 ln(L/B) + \beta_2 ln(B/T) + \beta_3 ln(C_B) + \beta_4 ln(S/L) \qquad (12)$$

The input dependent variables have now become natural logarithms of S/L, B/T, L/B and C_B, and the dependent variable is the natural logarithm of wave resistance coefficient C_W. The analysis was then carried out using *Statistica99* software package. The measured data from *SHIPFLOW* is shown in table 6 to table 9. The data was then transformed into natural logarithms to form the feeding independent variables for the regression analysis software – *Statistica99*.

(d) Analysis results

Regression analysis was conducted for all Froude numbers, table 10 briefly presents the partial outputs of the regression analysis at *Fn* = 1.0. The overall observation is that a high accuracy for the regression curve to fit in the data is achieved (R^2 generally greater than 99.5%). Table 11 gives the summary of regression coefficients. Substituting the values of $\alpha, \beta_1, \beta_2, \beta_3, \beta_4$ from table 11 in equation and taking inverse logarithms, we obtain:

$$C_W = exp(.911271) \times (L/B)^{-2.279982} \times (B/T)^{-1.317368} \times (C_B)^{0.979194} \times (S/L)^{0.004593} \qquad (13)$$

It should be emphasized again at this stage that the regression equation derived from the data may only be used to predict the performance of a new design that closely matches the character of the following points:

- The principal hull form parameters must fall within the range of values covered by the data.
- All other parameters must fall within the range of values covered by the data. This includes any predicted values of the dependant variables.
- When the data ships have a particular character the proposed ships must have the same character. This refers to factors such as the bow and stern profiles, hard-chine or round-bilge hull configuration, etc.

7.   Comparison of Results

The report by Molland et al. (1994) contains the total resistance coefficients for 13 test models, of which model 6c is selected for comparison. Wave resistance coefficients, C_W are shown in table 12. Frictional resistance coefficients are calculated using ITTC-1957 formula. Then C_W and C_F are substituted into equation (1) to find out the total resistance coefficient (C_T) for the model at the required Fn and demi-hull separation-length ratio. These C_T values are tabulated and can be compared with those of real test models recorded in the report. Figures 8 to 11 shows the graphical comparison of these two sets of data. It can be seen that both follow similar trends and good agreement is achieved between the two sets of results. There is still some noticeable margin of error, which may be attributed to the difference in hull form ie. chine-hull (research models) against round-bilge (test models), the possible deviation caused by the block coefficient of test models ($C_B = 0.397$) being well below the specified ranges for the application range of regression equations ($0.5 < C_B < 0.6$). Collectively, the regression equations predict relatively well the total resistance coefficients for catamaran having similar characteristics with the systematic series.

8.   Conclusions and Recommendations

- It is very useful to re-conduct the regression analysis on experimental data so as to achieve better regression equations.
- The validation of developed regression equations using hard-chine model test data is much appreciated. Corrections may be needed to account for trim effects and interference effects, which can only be better analysed by using towing tank test data.
- Integrating new geometric parameters such as deadrise angle and half angle of entrance into the regression analysis to observe their influences.
- Developing regression equations for lower range of Froude number (below 0.4) and at smaller Froude number increment (e.g. 0.05).

9.   Acknowledgments

10.   Nomenclature

L	Length between perpendiculars	C_T	Total Resistance Coefficient
B	Catamaran demi-hull beam	L_{WL}	Length at waterline
B_{WL}	Demi-hull beam at waterline	L_{OA}	Overall length
T	Draught	LCG	Longitudinal Centre of Gravity
C_W	Wave resistance coefficient	∇	Volume displacement

B/T	Beam-to-draught ratio	WSA/L^2	Dimensionless wetted surface area
L/B	Length-to-beam ratio	$(1+k)$	Form factor for the demi-hull in isolation.
$L/\nabla^{1/3}$	Slenderness ratio		
C_B	Block coefficient	τ	Wave resistance interference factor
C_F	Coefficient of frictional resistance	β	Viscous resistance interference factor
C_M	Midship section coefficient	β_M	Angle of deadrise amidships
C_P	Prismatic coefficient	g	Acceleration due to gravity (= 9.81 m/s^2)
Fn	Froude number		
Rn	Reynold's number	β_i	Regression coefficients
S	Catamaran demi-hull separation	α	Intercept in regression equation
S/L	Demi-hull separation-to-length ratio	ε_R	Residual drag to weight ratio
WSA	Wetted surface area		

11. References

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Parameter	Range
L/B	6 to 12
B/T	1 to 3
C_B	0.33 to 0.45
S/L	0.2, 0.3, 0.4 & 0.5
Fn	0.2 to 1.0

Table 1. Parameter Range as per Insel & Molland (1991)

		S/L = 0.2	S/L = 0.3	S/L = 0.4	S/L = 0.5
$L/\nabla^{1/3}$	B/T	$1 + \beta k$	$1 + \beta k$	$1 + \beta k$	$1 + \beta k$
8.5	1.5	1.44	1.43	1.44	1.47
8.5	2.0	1.41	1.45	1.40	1.38
8.5	2.5	1.41	1.43	1.42	1.44
Average		**1.42**	**1.44**	**1.42**	**1.43**
9.5	1.5	1.48	1.44	1.46	1.48
9.5	2.0	1.42	1.40	1.47	1.44
9.5	2.5	1.40	1.40	1.45	1.44
Average		**1.43**	**1.41**	**1.46**	**1.45**

Table 2. Form factors of catamarans (Molland et al. 1994).

Parameter	Range
Length	20 to 80 m
Displacement	25 to 1000 tonnes
Fn	0.8 to 1.4
L_{WL}/B_{XDH}	7.55 to 13.55
β_M	16° to 38°
δ_W	0° to 12°

Table 3. Parameter Range as per Muller-Graf (1993)

Geometric Parameters	Range
L/B	10 to 20
B/T	1.5 to 2.5
C_B	0.5 to 0.6
$L/\nabla^{1/3}$	6.6 to 12.6

Table 4. Range of Catamaran geometric parameters

Models	M1	M2	M 3	M 4	M 5	M 6	M 7	M 8	M 9	M 10	M 11	M 12	M 13	M 14	M 15	M 16	M17	M18
CB	0.50	0.50	0.50	0.50	0.50	0.55	0.55	0.55	0.55	0.55	0.60	0.60	0.60	0.60	0.60	0.60	0.55	0.59
L/B	10.40	10.40	15.60	20.80	20.80	10.40	15.60	15.60	15.60	20.60	10.40	10.40	15.60	15.60	20.80	20.80	13.00	17.20
B/T	1.50	2.50	2.00	1.50	2.50	2.00	1.50	2.00	2.50	2.00	1.50	2.50	1.50	2.00	1.50	2.50	1.86	1.60
L/$\nabla^{1/3}$	6.69	7.93	9.67	10.62	12.58	7.13	8.49	9.35	10.08	11.33	6.30	7.47	8.24	9.09	9.98	11.86	8.07	9.12
WSA/L²	0.16	0.12	0.09	0.08	0.06	0.14	0.11	0.09	0.08	0.07	0.17	0.13	0.11	0.09	0.08	0.06	0.11	0.10
β_M (deg)	23.14	23.20	26.68	22.96	23.25	23.80	26.43	23.80	19.15	23.80	24.53	16.21	24.02	20.58	24.02	16.21	24.53	24.66

Table 5. Model details

M 1   M 2   M 3   M 4   M 5

M 6   M 7   M 8   M 9   M 10

M 11   M 12   M 14   M 15   M 16

M 17   M 18   M 13
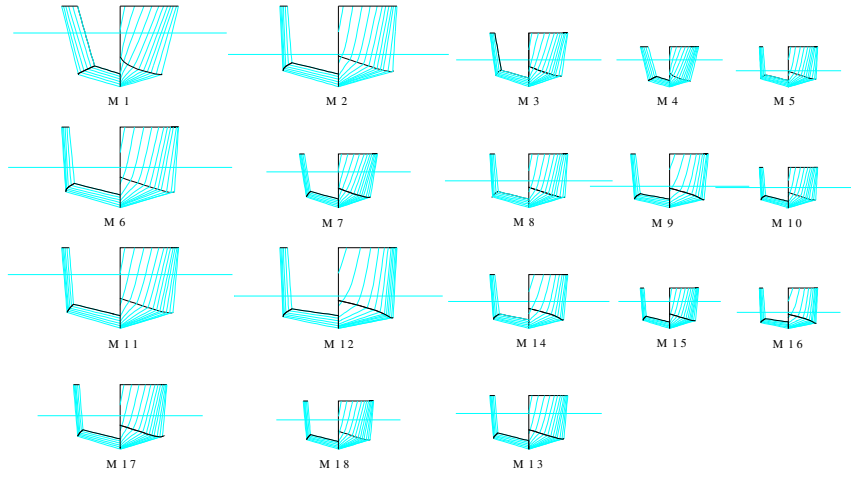
Figure 1. Body Plans of the Models

Baseline

A.P   ⊗   F.P
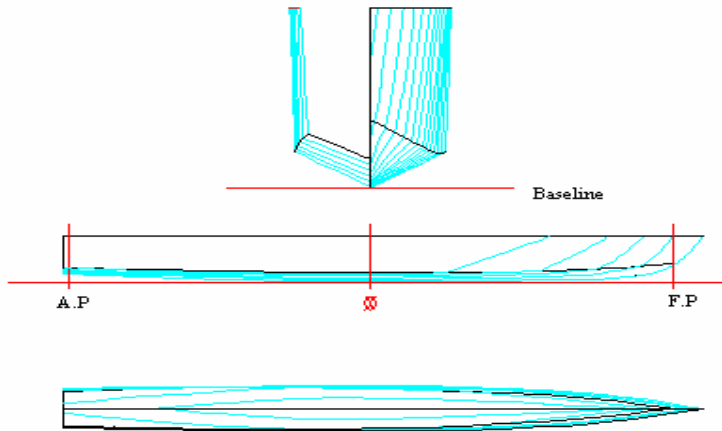
Figure 2. Model Lines Plan of the Parent Model, M8.

ZONE 1
Potential flow

ZONE 3
Navier-Stokes

ZONE 2
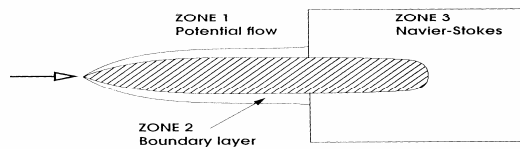Boundary layer

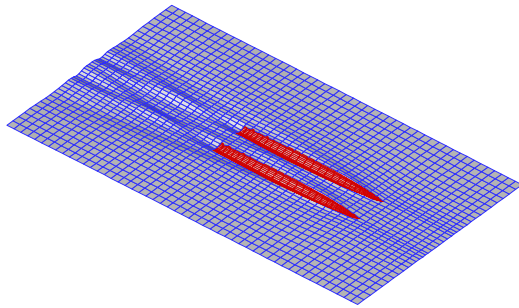Figure 3. The Zonal approach in *SHIPFLOW* (SHIPFLOW 2.3, 1997)

Figure 4. M17 (S/L=0.2, Fn = 1.0)
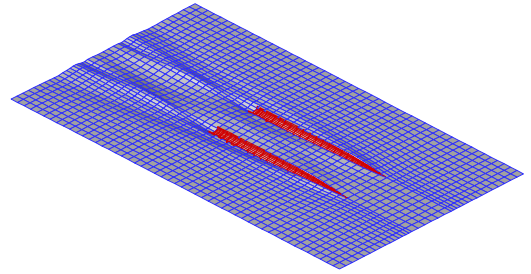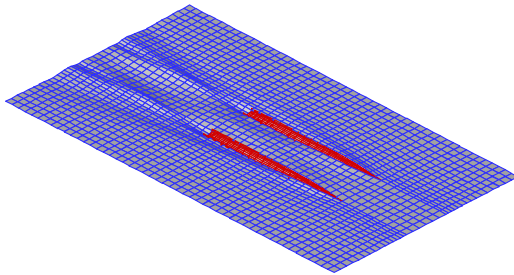

Figure 5. M17 (S/L=0.4, Fn = 1.0)

Figure 6. M17 (S/L=0.3, Fn = 1.0)
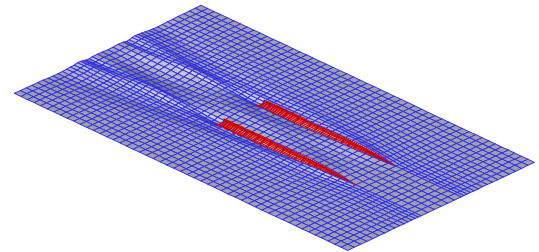
Figure 7. M17 (S/L=0.5, Fn = 1.0)

Fn Values	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
Model Number												
M 1	0.016	0.0182	0.0129	0.0086	0.006	0.0045	0.0036	0.0029	0.0025	0.0022	0.0019	0.0017
M 2	0.0064	0.0086	0.0062	0.0042	0.0029	0.0022	0.0018	0.0015	0.0013	0.0012	0.0011	0.001
M 3	0.004	0.0044	0.0031	0.0021	0.0015	0.0012	0.001	0.0008	0.0007	0.0006	0.0006	0.0005
M 4	0.0034	0.0033	0.0023	0.0016	0.0012	0.0009	0.0008	0.0006	0.0006	0.0005	0.0004	0.0004
M 5	0.0013	0.0015	0.001	0.0007	0.0005	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
M 6	0.0107	0.0129	0.0094	0.0064	0.0045	0.0033	0.0026	0.0022	0.0019	0.0016	0.0015	0.0013
M 7	0.0074	0.0073	0.0051	0.0035	0.0025	0.0019	0.0015	0.0013	0.0011	0.0009	0.0008	0.0007
M 8	0.0043	0.0048	0.0034	0.0023	0.0017	0.0013	0.001	0.0009	0.0008	0.0007	0.0006	0.0005
M 9	0.0027	0.0032	0.0024	0.0016	0.0012	0.0009	0.0008	0.0007	0.0006	0.0006	0.0005	0.0005
M 10	0.0023	0.0024	0.0017	0.0011	0.0008	0.0007	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003
M 11	0.0191	0.0202	0.0148	0.0101	0.0071	0.0053	0.0041	0.0034	0.0028	0.0023	0.0019	0.0016
M 12	0.0072	0.0094	0.0073	0.005	0.0035	0.0027	0.0022	0.0019	0.0017	0.0016	0.0015	0.0017
M 13	0.0044	0.005	0.0037	0.0025	0.0018	0.0014	0.0012	0.001	0.0009	0.0008	0.0007	0.0007
M 14	0.0042	0.004	0.0028	0.0019	0.0014	0.0011	0.0009	0.0008	0.0006	0.0006	0.0005	0.0004
M 15	0.0015	0.0017	0.0012	0.0009	0.0007	0.0005	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003
M 16	0.0076	0.0084	0.006	0.0041	0.0029	0.0022	0.0018	0.0015	0.0013	0.0011	0.001	0.0009
M 17	0.0048	0.0049	0.0035	0.0024	0.0017	0.0013	0.0011	0.0009	0.0008	0.0007	0.0006	0.0005
M 18	0.0079	0.0078	0.0056	0.0038	0.0028	0.0021	0.0017	0.0014	0.0012	0.001	0.0009	0.0008

Table 6. Wave Resistance Coefficient (C_w) from SHIPFLOW at S/L ratio of 0.2

Fn Values	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
Model Number												
M1	0.0159	0.0156	0.0109	0.0075	0.0056	0.0044	0.0036	0.003	0.0026	0.0022	0.0019	0.0017
M 2	0.0068	0.0073	0.0051	0.0036	0.0027	0.0021	0.0018	0.0015	0.0014	0.0012	0.0011	0.001
M 3	0.0042	0.0038	0.0027	0.0019	0.0015	0.0012	0.001	0.0008	0.0007	0.0006	0.0005	0.0005
M 4	0.0034	0.0029	0.0021	0.0015	0.0011	0.0009	0.0008	0.0007	0.0006	0.0005	0.0004	0.0004
M 5	0.0013	0.0013	0.0009	0.0006	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0002
M 6	0.011	0.0113	0.0079	0.0055	0.0041	0.0032	0.0026	0.0022	0.0019	0.0017	0.0015	0.0013
M 7	0.0075	0.0066	0.0046	0.0032	0.0024	0.0019	0.0015	0.0013	0.0011	0.0009	0.0008	0.0007
M 8	0.0045	0.0042	0.003	0.0021	0.0016	0.0013	0.0011	0.0009	0.0008	0.0007	0.0006	0.0005
M 9	0.0029	0.0028	0.002	0.0015	0.0011	0.0009	0.0008	0.0007	0.0006	0.0006	0.0005	0.0005
M 10	0.0024	0.0021	0.0015	0.0011	0.0008	0.0007	0.0006	0.0005	0.0004	0.0004	0.0003	0.0003
M 11	0.0192	0.0182	0.0129	0.0089	0.0065	0.005	0.0041	0.0034	0.0028	0.0023	0.002	0.0016
M 12	0.0075	0.0085	0.0061	0.0043	0.0032	0.0026	0.0022	0.0019	0.0017	0.0016	0.0015	0.0017
M 13	0.0046	0.0045	0.0032	0.0023	0.0017	0.0014	0.0012	0.001	0.0009	0.0008	0.0007	0.0006
M 14	0.0043	0.0036	0.0025	0.0018	0.0014	0.0011	0.0009	0.0008	0.0007	0.0006	0.0005	0.0004
M 15	0.0016	0.0015	0.0011	0.0008	0.0006	0.0005	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003
M 16	0.0078	0.0075	0.0052	0.0036	0.0027	0.0022	0.0018	0.0015	0.0013	0.0011	0.001	0.0009
M 17	0.005	0.0044	0.0031	0.0022	0.0017	0.0013	0.0011	0.0009	0.0008	0.0007	0.0006	0.0005
M 18	0.008	0.0071	0.005	0.0035	0.0026	0.0021	0.0017	0.0014	0.0012	0.001	0.0009	0.0008

Table 7. Wave Resistance Coefficient (C_w) from SHIPFLOW at S/L ratio of 0.3

Fn Values	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
Model Number												
M1	0.0153	0.0141	0.0102	0.0074	0.0056	0.0044	0.0036	0.003	0.0025	0.0022	0.0019	0.0016
M 2	0.0066	0.0065	0.0048	0.0035	0.0027	0.0022	0.0018	0.0015	0.0013	0.0012	0.0011	0.001
M 3	0.004	0.0035	0.0026	0.0019	0.0015	0.0012	0.001	0.0008	0.0007	0.0006	0.0005	0.0005
M 4	0.0033	0.0027	0.002	0.0015	0.0012	0.0009	0.0008	0.0006	0.0006	0.0005	0.0004	0.0004
M 5	0.0013	0.0012	0.0009	0.0006	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0002
M 6	0.0108	0.0102	0.0074	0.0053	0.0041	0.0032	0.0027	0.0022	0.0019	0.0016	0.0014	0.0013
M 7	0.0074	0.0061	0.0044	0.0032	0.0024	0.0019	0.0015	0.0013	0.0011	0.0009	0.0008	0.0007
M 8	0.0044	0.0039	0.0028	0.0021	0.0016	0.0013	0.0011	0.0009	0.0008	0.0007	0.0006	0.0005
M 9	0.0028	0.0026	0.0019	0.0014	0.0011	0.0009	0.0008	0.0007	0.0006	0.0006	0.0005	0.0005
M 10	0.0023	0.0019	0.0014	0.0011	0.0008	0.0007	0.0006	0.0005	0.0004	0.0004	0.0003	0.0003
M 11	0.0189	0.0167	0.0121	0.0086	0.0064	0.005	0.0041	0.0034	0.0028	0.0023	0.0019	0.0016
M 12	0.0076	0.0076	0.0056	0.0042	0.0032	0.0027	0.0022	0.0019	0.0017	0.0016	0.0016	0.0019
M 13	0.0046	0.0041	0.003	0.0022	0.0017	0.0014	0.0012	0.001	0.0009	0.0008	0.0007	0.0006
M 14	0.0042	0.0034	0.0025	0.0018	0.0014	0.0011	0.0009	0.0008	0.0006	0.0006	0.0005	0.0004
M 15	0.0016	0.0014	0.001	0.0008	0.0006	0.0005	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003
M 16	0.0078	0.0075	0.0052	0.0036	0.0027	0.0022	0.0018	0.0015	0.0013	0.0011	0.001	0.0009
M 17	0.0049	0.0041	0.003	0.0022	0.0017	0.0013	0.0011	0.0009	0.0008	0.0007	0.0006	0.0005
M 18	0.0079	0.0066	0.0048	0.0035	0.0026	0.0021	0.0017	0.0014	0.0012	0.001	0.0009	0.0008

Table 8. Wave Resistance Coefficient (C_w) from SHIPFLOW at S/L ratio of 0.4

Fn Values	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
Model Number												
M1	0.0145	0.0134	0.01	0.0073	0.0056	0.0044	0.0035	0.0029	0.0025	0.0021	0.0018	0.0015
M 2	0.0062	0.0061	0.0047	0.0035	0.0027	0.0022	0.0018	0.0015	0.0013	0.0012	0.0011	0.001
M 3	0.0039	0.0034	0.0025	0.0019	0.0015	0.0012	0.001	0.0008	0.0007	0.0006	0.0005	0.0005
M 4	0.0032	0.0027	0.002	0.0015	0.0012	0.0009	0.0008	0.0006	0.0005	0.0005	0.0004	0.0004
M 5	0.0012	0.0011	0.0009	0.0006	0.0005	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
M 6	0.0103	0.0096	0.0072	0.0053	0.0041	0.0032	0.0026	0.0022	0.0019	0.0016	0.0014	0.0013
M 7	0.0072	0.0059	0.0043	0.0032	0.0024	0.0019	0.0015	0.0013	0.0011	0.0009	0.0008	0.0007
M 8	0.0042	0.0037	0.0028	0.0021	0.0016	0.0013	0.001	0.0009	0.0007	0.0006	0.0006	0.0005
M 9	0.0027	0.0025	0.0019	0.0014	0.0011	0.0009	0.0008	0.0007	0.0006	0.0006	0.0005	0.0005
M 10	0.0022	0.0019	0.0014	0.0011	0.0008	0.0007	0.0006	0.0005	0.0004	0.0004	0.0003	0.0003
M 11	0.0183	0.0159	0.0118	0.0086	0.0065	0.005	0.004	0.0033	0.0028	0.0023	0.0019	0.0016
M 12	0.0073	0.0071	0.0055	0.0042	0.0033	0.0027	0.0022	0.0019	0.0017	0.0016	0.0016	0.0019
M 13	0.0045	0.0039	0.003	0.0022	0.0017	0.0014	0.0012	0.001	0.0009	0.0008	0.0007	0.0006
M 14	0.0041	0.0033	0.0024	0.0018	0.0014	0.0011	0.0009	0.0008	0.0006	0.0005	0.0005	0.0004
M 15	0.0015	0.0014	0.001	0.0008	0.0006	0.0005	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003
M 16	0.0074	0.0065	0.0049	0.0036	0.0027	0.0022	0.0018	0.0015	0.0013	0.0011	0.0009	0.0008
M 17	0.0047	0.004	0.0029	0.0022	0.0017	0.0013	0.0011	0.0009	0.0008	0.0007	0.0006	0.0005
M 18	0.0077	0.0064	0.0047	0.0035	0.0026	0.0021	0.0017	0.0014	0.0012	0.001	0.0009	0.0007

Table 9. Wave Resistance Coefficient (C_w) from SHIPFLOW at S/L ratio of 0.5

Regression Summary for Dependent Variable: $ln(Cw)$ at $Fn = 1.0$					
R= .99865017		R^2= .99730217		Adjusted R^2= .99714110	
$F(4,67)$=6191.9	p<0.0000			Std.Error of estimate: 0.03540	
	BETA	St. Err. of BETA	B	St. Err.of B	t(67)	p-level
Intercept			0.911271	0.058404	15.60276	5.37E-24
Ln(S/L)	0.002393	0.006346	0.004593	0.012178	0.377187	0.707226
Ln(L/B)	-0.913372	0.006352	-2.279982	0.015856	-143.7930	0.000000
Ln(B/T)	-0.410460	0.006408	-1.317368	0.020567	-64.05308	0.000000
Ln(C_B)	0.107555	0.006410	0.979194	0.058359	16.77888	1.1E-25

Table 10. Outputs of Regression Analysis for Fn = 1.0

Fn	α	β_1	β_2	β_3	β_4
0.4	2.507751	-2.255878	-1.819332	0.921796	-0.026670
0.5	2.448887	-2.424720	-1.582805	0.861936	-0.278595
0.6	2.231476	-2.442478	-1.528469	0.931836	-0.232555
0.7	1.898569	-2.402987	-1.489982	0.961013	-0.129839
0.8	1.543052	-2.351095	-1.442334	0.965683	-0.046904
0.9	1.208420	-2.308691	-1.384697	0.966650	-0.004858
1	0.911271	-2.279982	-1.317368	0.979194	0.004593
1.1	0.063404	-2.257688	-1.240560	0.995197	-0.004378
1.2	0.391235	-2.242743	-1.155136	1.021166	-0.017454
1.3	0.162273	-2.233282	-1.050167	1.036256	-0.027712
1.4	0.002700	-2.235047	-0.908676	1.119485	-0.031137
1.5	-0.028588	-2.268397	-0.692935	1.326583	-0.035505

Table 11. Summary of Regression Coefficients

	S/L=0.2	S/L=0.3	S/L=0.4	S/L=0.5	S/L=0.2	S/L=0.3	S/L=0.4	S/L=0.5
Fn	Regression	Regression	Regression	Regression	Test	Test	Test	Test
0.40	0.008052	0.008371	0.008234	0.008086	0.007653	0.007743	0.007782	0.007598
0.50	0.009561	0.008476	0.008013	0.00785	0.007952	0.007517	0.007325	0.007244
0.60	0.00769	0.007151	0.006896	0.006802	0.006747	0.006521	0.006532	0.006517
0.70	0.006516	0.006516	0.00624	0.006171	0.006064	0.005998	0.005992	0.006047
0.80	0.005937	0.005986	0.005825	0.005816	0.005637	0.005671	0.005703	0.005769
0.90	0.005679	0.005724	0.005556	0.005555	0.005505	0.005517	0.00557	0.005623
1.00	0.005422	0.005492	0.00546	0.00535	0.005398	0.005466	0.005488	0.005524

Table 12. Comparison of Model Test data of Molland et al. [1994] against Regression Method.
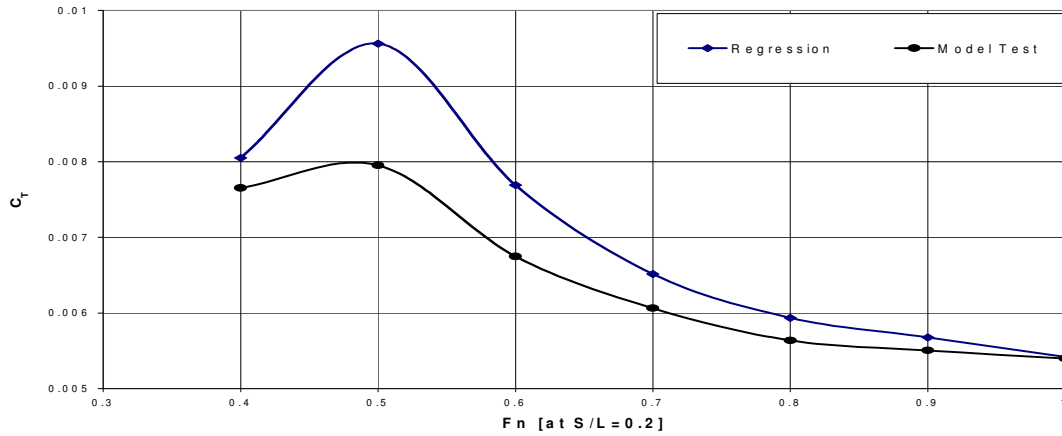

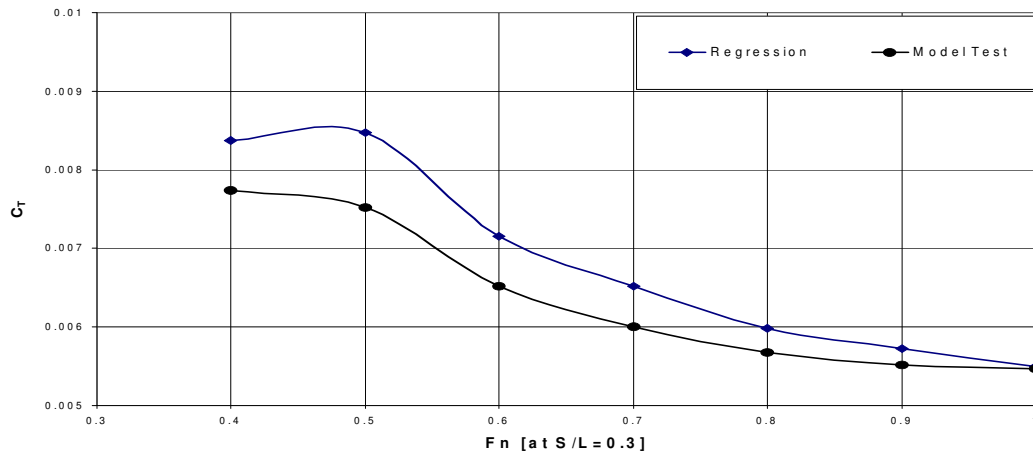Figure 8. Comparison between Experimental and regression results for Model 6C (S/L=0.2)

Figure 9. Comparison between Experimental and regression results for Model 6C (S/L=0.3)
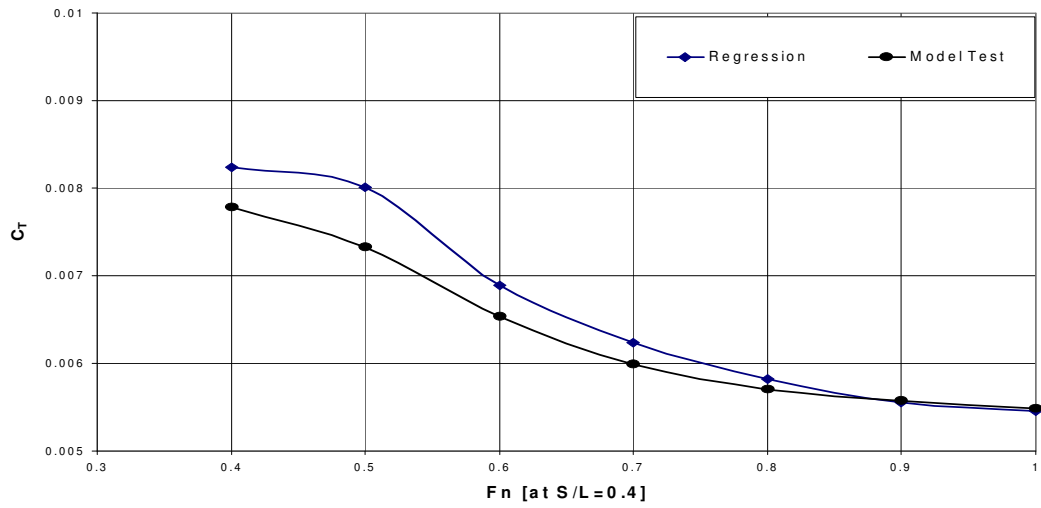
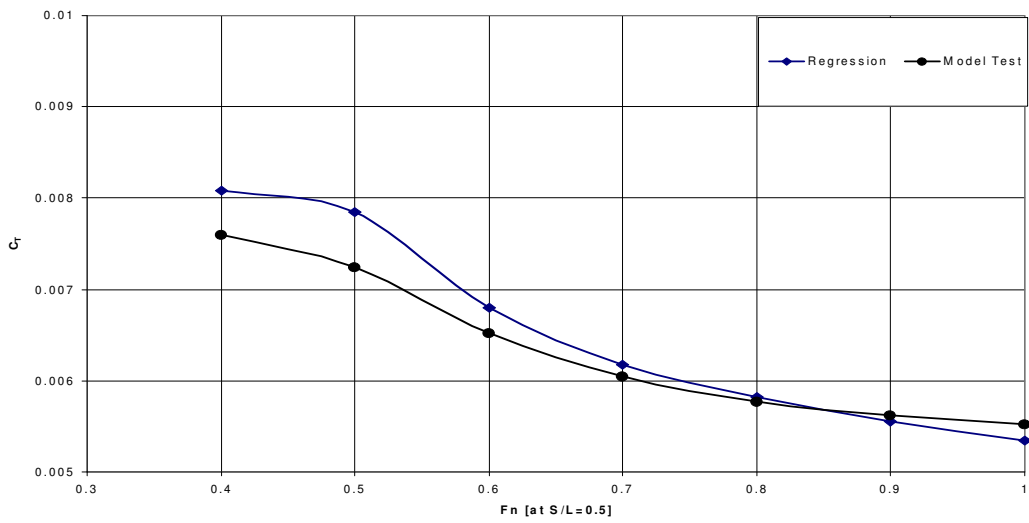Figure 10. Comparison between Experimental and regression results for Model 6C (S/L=0.4)

Figure 11. Comparison between Experimental and regression results for Model 6C (S/L=0.5)