A NUMERICAL METHOD FOR PERFORMANCE PREDICTION OF HYDROFOIL-ASSISTED CATAMARANS

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SUMMARY

A numerical method for predicting the performance of foil-assisted catamarans will be described in the paper and the results compared with experimental data. The method developed is extremely flexible, in that it is able to account for any configuration of foils and hull shape. This will allow a wide range of parameters to be tested in the preliminary design of a foil-assisted catamaran.

AUTHORS' BIOGRAPHIES

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Lawrence Doctors has lectured at UNSW since 1971. During his career, most of Professor Doctors' research efforts have been devoted to numerical ship hydrodynamics, where his interests include the study of advanced marine vehicles. He is currently Professor and Coordinator of the Naval Architecture Program at UNSW.

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Dr Paul Brandner has been working in experimental and numerical hydrodynamics for over 13 years. His research interests include ship dynamics, cavitation, two-phase flows and viscous flows. He is currently manager of the Cavitation Tunnel at AMC.

NOMENCLATURE

A	Aspect ratio, S/c
c	Chord length of foil
C_{DI}	Coefficient of induced drag
C_L	Coefficient of lift, $L_F/(\frac{1}{2}\rho U^2 cS)$
D_F	Foil Drag
F_z	Force in the z direction
I_W	Wave-interference factor
L_F	Foil lift
LCF	Longitudinal centre of flotation
LCG	Longitudinal centre of gravity
M_{LCF}	Moment about the LCF
M_P	Pressure moment on demihull
R_{fr}	Frictional-resistance force
R_P	Pressure-resistance force
$R_{W,\mathrm{cat}}$	Wave resistance of a catamaran
$R_{W,\mathrm{demi}}$	Wave resistance of a demihull in isolation
S	Foil span
S_P	Sinkage-pressure force on demihull
T_N	Nominal Draft
U	Free-stream velocity
W	Weight of the vessel
x_F	Longitudinal lever arm for the foil lift
x_P	Longitudinal lever arm for the pressure sinkage force
x_{prop}	Longitudinal lever arm for the propulsion force
X_{prop}	Longitudinal component of the propulsion force
Z_{fr}	Vertical lever arm for the frictional force
z_F	Vertical lever arm for the foil drag
z_P	Vertical lever arm for pressure-resistance force
z_{prop}	Vertical lever arm for the propulsion force
Z_{prop}	Vertical component of the propulsion force
ρ	Density of water
τ	Trim of the vessel in degrees

1 INTRODUCTION

1.1 BACKGROUND

Research into the area of hydrofoil assistance for high-speed vessels has been ongoing for many years, and several researchers have shown that large reductions in resistance are possible. The potential benefits of foil assistance also include improved seakeeping characteristics; this is certainly a desirable outcome for many fast-ferry operators that merits further investigation.

The task of designing an efficient foil-assisted catamaran (FAC) is not a simple one. Most vessels that have been built to date have been backed up with a programme of experimental testing and varying degrees of theoretical work. Despite the lure of large reductions in resistance, the possibility of increased resistance also looms in front of a designer. It thus becomes important to be able to predict and optimise the resistance of a design prior to, or without, model testing.

An understanding of the components of resistance of a FAC is essential. We aim to present a method which allows the designer to evaluate the trends that are apparent in the variation of the various design parameters, *i.e.* number of foils and their size, longitudinal and vertical position of foils and loading condition.

1.2 PREVIOUS WORK

Hoppe has conducted a lot of research into the Hydrofoil-Supported Catamaran (HYSUCAT) design through extensive model testing and he described a theoretical model in [1]. The resistance-prediction technique calculates the foil forces using a combination of aerofoil theory and empirical corrections, whilst the hull forces are calculated using the semi-empirical planing formulations of Savitsky [2]. Hoppe also stated that the developed computer program corrects for interference of the foils on the demihulls, but did not elaborate on how this is done.

Miyata [3] published the results of a series of model tests conducted on foil-assisted catamarans. Twin V-shaped hulls were tested with two foils in varying configurations. Reproducible data is published in this paper for the resistance, dynamic trim and sinkage of the models. Miyata clearly showed that the vessels tested benefit from foil assistance in the form of reduced resistance and improved seakeeping characteristics.

Migeotte *et al.* [4] discussed further improvement of their computer model where they modelled the foils using a non-linear vortex lattice method. The hulls were modelled using a planing surface. It is claimed that this method also shows consistent results in the transition to the planing phase, but does not indicate the success when a semi-displacement (round bilge) hull is used.

Shimizu *et al.* [5] conducted a series of experiments to evaluate the resistance components of a catamaran with two foils. Lift, drag and pitching moment were measured on the hull and each foil independently for fixed values of dynamic sinkage and trim. A computer program was created to calculate the resistance tendencies of the vessel using the experimental data. The experimental data showed that the lift of the aft foil had a greater effect on the hull resistance than that of the forward foil. The reasons for this occurring were not discussed.

Tsai *et al.* [6] tested two foil-assisted models with two different foil configurations, a tandem and a single foil configuration. Two components of force, namely lift and drag, were measured from each foil; however the authors did not elaborate on the method and instrumentation used in obtaining this data.

1.3 CURRENT AIMS

To date, no research has been devoted to the numerical investigation of the resistance of a foil-assisted catamaran with semi-displacement hulls. This is most likely due to the lack of numerical methods that are able to quickly and accurately evaluate both the resistance of catamarans and the sinkage forces and trimming moments on a round-bilge hull.

The aim of the research has been to create a calculation method able to evaluate the resistance and running condition of a foil-assisted catamaran with semi-displacement demihulls.

For design purposes, it is important to be able to get quick feedback on the effect of changing foil configuration. Foil section type and location is likely to be changed more often in the quest for better performance or avoidance of cavitation.

Hull shape is a more complex parameter and more likely to stay the same through the design spiral. This is especially relevant to retrofit cases. Thus, the method for calculating hull resistance is permitted to be time consuming, as it only needs to be performed once. This also presents the opportunity to derive hull forces from suitable experimental data, *i.e.* tests where sinkage forces and trim moments are measured in addition to resistance for a range of values of dynamic trim and draft.

2 THEORETICAL WORK

For the purposes of the numerical method and future analysis, the forces acting on a hydrofoil-assisted catamaran are considered to come from two separate entities: the foils and the hulls. Two previously existing computer programs that calculate the forces from these two entities have been integrated together to form a program that calculates the resistance, sinkage and trim of a vessel at any speed.

2.1 HYDROFOIL FORCES

The forces from the hydrofoils are calculated using a method outlined by Andrewartha and Doctors [7]. The program solves the flow over two-dimensional hydrofoils operating near the free surface using a panel method. Viscous effects are accounted for by using an iterative method to interact the calculated boundary layers and potential flow solution.

An advantage of this method is that it is able to account for the downwash angle induced by the bow foil on a stern foil. It is anticipated that due to the flow over the foils being bounded by the demihulls, the two-dimensional simplification will be reasonably accurate for calculations of lift and drag.

To calculate the forces on a three-dimensional hydrofoil, several corrections are made to the forces calculated for the foil section. Lifting-line theory provides the basis for a correction to allow for finite aspect ratio [8]. Glauert [9, p. 150] gives a correction to the lift to convert the assumed elliptic load distribution to the actual rectangular one.

Induced drag is added to the section drag using Equation 1, whilst a correction for the drag of bare tips can be made if they exist. However, the foils on a foil-assisted catamaran are usually bounded by struts or the sides of the demihulls.

$$C_{DI} = \frac{C_L^2}{\pi A} \quad (1)$$

2.2 HULL FORCES

The forces acting on the hull are calculated using the method outlined by Doctors and Day [10]. The near-field solution for the flow must be found in order to calculate the sinkage and trim, while wave resistance is calculated using the far-field theory described by Michell [11]. This method has been shown to predict the resistance of semi-displacement catamarans with good accuracy.

For the FAC prediction program, it is necessary to perform calculations for resistance, sinkage force and pressure moment only once. The output is stored in a file which is input as a matrix to the FAC prediction program. Bilinear interpolation is used to find values for arbitrary dynamic trim and draft, within the specified limits.

2.3 FOIL-ASSISTED CATAMARAN FORCES

The output from the foil and hull methods are combined in a program that iteratively solves for the equilibrium values of sinkage and trim at any vessel speed.

To find equilibrium in the vertical direction, the vertical forces are summed together:

$$\sum F_z = -S_P - W + Z_{\text{prop}} + \sum L_{Fi} \quad (2)$$

For moment equilibrium, moments about the LCF are summed, as in Equation 3. Figure 1 shows the locations and definitions of the variables used.

$$\begin{aligned}\sum M_{\text{LCF}} &= -M_P - z_P R_P + (x_p - \text{LCF}) S_P \\ &- (x_{\text{prop}} - \text{LCF}) Z_{\text{prop}} + z_{\text{prop}} X_{\text{prop}} \\ &- z_{fr} R_{fr} + (\text{LCG} - \text{LCF}) W - \sum (x_{Fi} L_{Fi} + z_{Fi} D_{Fi})\end{aligned} \quad (3)$$

The hull forces in Equations 2 and 3 are calculated as described in Section 2.2, whilst the foil forces are calculated during each iteration within the FAC prediction program. In order to find the equilibrium position, the computer program uses a two-dimensional Newton-Raphson method to adjust the trim and draft. Three function evaluations for every iteration are required in order to calculate the partial derivatives.

This iteration process converges very rapidly due to the linear relation between both trim and foil lift, and buoyancy and draft. Figure 2 plots an example of the values of moment and vertical force as functions of dynamic trim and draft.

The process is generally run for a range of speeds, starting at the lowest speed. Trim and sinkage are smallest at the lowest speed and hence the initial estimates of T_N and τ are those from the static case. To aid convergence, each subsequent speed uses the values of trim and draft from the previous speed as the starting point for the iteration process.

Convergence occurs when the non-dimensionalised net vertical force and moment are less than some arbitrary tolerance, or when the calculated changes in trim and non-dimensional draft are less than a specified amount. The method generally converges to a relative tolerance of 10^{-6} within four iterations.

2.4 INTERACTIONS BETWEEN THE DEMIHULLS AND FOILS

By considering the forces on the hulls and foils separately, we are effectively ignoring the interactions between the two entities. The interactions are assumed to be of two types: viscous and wave effects.

Whilst the wave systems from the hulls and foils have been considered to calculate the wave resistance of each, the interaction of the two wave systems is more difficult to evaluate and has not been considered in the current method. It is encouraging to note that at high speeds, the wave resistance of a foil-assisted catamaran is steadily decreasing due to the increased Froude number and reduction in immersed hull volume.

However, it is possible to calculate one interaction between the foils and demihulls. The hydrofoil creates a surface wave between the demihulls and this increases the wetted-surface area of the demihulls and hence the frictional drag. As a result, the method has been adapted to include this effect.

The viscous interactions are rather more difficult to ascertain using the current theory, and have been ignored.

3 COMPARISON WITH EXPERIMENTAL DATA

3.1 BARE-HULL TESTS

A series of standard resistance tests was conducted on a bare hull for comparison with foil-assisted tests. This allowed evaluation of the resistance change when using foil assistance, and also validation of the theory for a bare hull.

A semi-displacement hull at scale 1:20 was tested at various displacements and static trims. A body plan of a demihull is given in Figure 3. Five displacements were tested, varying from 70% to 100% of full-load displacement. Static trim was varied from -1.0° to 1.0° in 0.5° increments.

Figures 5, 6 and 7 and show a comparison of the experimental data with results from the FAC prediction program for a case with no foils. The theory shows reasonable agreement with the experimental data, except near the hump region. The theory over predicts the resistance and under predicts the sinkage and trim at hump speed. This can be attributed to two different factors.

The implication of using the FAC prediction program is that we are including the effects of sinkage and trim into the calculation, while Doctors and Day showed that the method is more accurate when sinkage and trim are not included. Theoretical data from this linear method is also included in Figure 5.

Using non-zero values of sinkage and trim is a departure from the consistent linear theory of Michell. Whilst one would expect that this should improve the relation between theory and experiment, we are neglecting the other major non-linear effect, namely the free-surface distortion. For this reason, it is anticipated that this approximation to a non-linear method is the reason for the discrepancy in the resistance values at hump speed.

The discrepancy between the sinkage and trim values is due to the interference of the demihull wave systems at hump speed. The resistance values are calculated using the far-field theory which accounts for the wave interference in a consistent manner. However, it is necessary to use near-field theory to calculate the pressure distribution (and hence sinkage force and trimming moment) over the demihulls, and these calculations do not account for the wave interference.

The effect of the wave interference on sinkage and trim can be accounted for to some extent by examining the difference between the resistance of a demihull in isolation and of the catamaran. By this we define a wave-interference factor, I_W as in Equation 4.

$$I_W = \frac{R_{W,\mathrm{cat}}}{2R_{W,\mathrm{demi}}} \quad (4)$$

The wave interference is a function of Froude number, and can be derived from the theory described in Section 2.2. If we multiply the sinkage and trim values by I_W, the fit is much closer as shown in Figure 6 and Figure 7. While this is not the recommended method for calculating sinkage and trim, the close match in the slopes at hump speed demonstrates that wave interaction should be accounted for in the calculation of pressure distribution in some manner.

3.2 BARE-FOIL TESTS

Tests on a single hydrofoil using a six-component force balance were conducted to measure forces from a bare foil. The test matrix involved varying the speed, depth and angle of attack of the foil. The foil spanned two faired struts that were attached to the tips of the foil and the outside of the force balance. The type of foil section to be used was originally a NACA 4412 section, but this was modified upon fabrication to a slightly thicker section. The profile of this as-built section was measured and offsets are given in Table 1. This explains the non-zero ordinates at station 0, the leading edge, and station 60, the trailing edge.

The NACA 4412 section was chosen as it showed consistent performance at low Reynolds number through analysis with the XFOIL program [12]. The foil chord was 60 mm, span was 325 mm and a range of speeds between 0.5 and 4 m/s were tested. The angle of attack was varied from -4 degrees to 4 degrees in one degree increments and the depth varied from 30 mm (half the chord) to 180 mm (three chords) in half-chord increments.

Tests on the bare struts were also conducted to calculate tare values. Speed and depth of strut were varied over the same range as the foil tests. These tests enabled the calculation of the drag for the hydrofoil section as well as the drag for the struts as a function of strut depth.

Two samples of the results from the bare-foil experiments are plotted in Figures 8 and 9. Plotted against this for comparison are results from the numerical foil program. The numerical data has been corrected in the manner discussed in Section 2.1, and the effective aspect-ratio is increased due to the end-plate effect of the struts. The effective aspect-ratio has been calculated using the data presented by Wadlin [13, Figure 27].

The drag values have also been corrected to allow for the model-scale Reynolds numbers. The values of viscous drag calculated by the current foil method are not applicable at these very low Reynolds numbers (around 10^5). Instead, the viscous drag has been calculated by the XFOIL program. The method used by XFOIL is able to handle small regions of laminar separation which may be present at model-scale Reynolds numbers.

By making the above corrections, the theoretical predictions show good agreement with the experimental data in Figures 8 and 9.

3.3 FOIL-ASSISTED CATAMARAN TESTS

Experimental tests were conducted on a foil-assisted catamaran with one foil (NACA 4412mod section, see Table 1) located 10 mm below the keel at the LCG. The model was tested for the same displacements as the bare-hull tests (Section 3.1). The angle of attack of the foil was also varied between -3° and 4°.

A force balance sat atop the demihulls and the struts extended down through rectangular slots cut into the keel of each demihull, Figure 4. This way the force from the foil was transmitted entirely through the force balance to the hulls.

Figure 10 plots the experimental drag values against speed for the 100% displacement load case. The foil drag was measured using a six-component balance and the hull drag is calculated as the difference between total drag and foil drag.

Also plotted in Figure 10 are predictions from the theoretical program discussed in Section 10. The predictions have been made at model scale and the viscous foil drags corrected using values predicted by the XFOIL program.

The theoretical predictions are quite reasonable; the foil drag is predicted with good accuracy and the hull drag is quite close to the drag measured in the experiments near the hump speeds. At higher speeds, the theoretical hull drag is less than that measured experimentally presumably because of spray drag. Spray was observed during the experiments. This is also seen in the bare-hull data (see Figure 5).

The predicted values of sinkage and trim are plotted in Figure 11. The theoretical sinkage matches the experimental data, while the trim at hump speed is not predicted well due to the reasons discussed in Section 3.1.

The lift force from the foil is plotted for theory and experiment in Figure 12. The agreement is excellent, similar to the agreement of the drag predictions. Even at the hump speed, the absolute accuracy is quite good, despite the fact that the theoretical trim is different. This indicates that the major factors affecting foil lift are speed and submergence.

Plotted in Figure 13 is a comparison of the theoretical hull drag with and without the interaction effect of the foil surface-wave on frictional resistance (Section 2.4). At high speeds, where the frictional resistance dominates, the difference between the two is quite large (around 20%). At the hump speed, the agreement between theory and experiment is also improved when the foil surface-wave is taken into account.

4 CONCLUSIONS

4.1 CURRENT WORK

The drag and lift of the foil is predicted with good accuracy by the theory, both with and without the influence of the demihulls. To a certain extent, this indicates that two of the assumptions made in the theory are validated, as described next.

The results show that the hull has a minimal effect on the foil flow. This goes some way to validating the lack of interaction effects accounted for by the theoretical method. Additionally, the assumption of two-dimensional flow is shown to be useful in calculating the macroscopic properties of the flow, *i.e.* lift and drag coefficients.

The theory used to predict the hull forces has also been validated. However it would be desirable to have a method that was able to account for the dynamic sinkage and trim in a more consistent manner. It would also be desirable to be able to calculate the drag due to spray.

A numerical resistance-prediction program has been developed and shown that it is capable of predicting the resistance of a FAC within reasonable accuracy. It has been shown that a significant interaction occurs between the foil and hull; the frictional resistance of the demihulls is increased due to the surface wave produced by foil.

4.2 FURTHER WORK

Future work in the field should include the interactions between the wave systems of the hulls and foils in more detail. These effects have been mostly ignored by the current method, but should be considered for more accurate analyses in the future.

It would be extremely beneficial to investigate the flow near the foil-hull junctions using a Navier-Stokes solver with experimental work to back it up. It may not be necessary to have a free surface to look at the viscous effects experimentally; the work could be carried out at a larger scale (more realistic Reynolds number) in a facility such as a cavitation tunnel.

5 ACKNOWLEDGEMENTS

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Upper Surface		Lower Surface	
Station [mm]	Ordinate [mm]	Station [mm]	Ordinate [mm]
0	0.75	0	0.00
6	2.14	1	-0.01
8	2.51	2	-0.01
10	2.94	3	-0.02
12	3.45	4	-0.03
14	3.84	5	-0.04
16	4.21	6	-0.06
18	4.56	8	-0.08
20	4.88	10	-0.12
22	5.17	12	-0.14
24	5.45	14	-0.20
26	5.70	16	-0.24
28	5.94	18	-0.29
30	6.14	20	-0.38
32	6.31	22	-0.45
34	6.44	24	-0.52
35	6.50	26	-0.59
36	6.54	28	-0.67
37	6.56	30	-0.75
38	6.58	32	-0.82
39	6.58	34	-0.92
40	6.57	36	-0.99
41	6.54	38	-1.09
42	6.51	40	-1.18
43	6.46	42	-1.28
44	6.39	44	-1.36
45	6.30	46	-1.46
46	6.18	48	-1.55
47	6.08	50	-1.64
48	5.94	52	-1.68
49	5.78	53	-1.69
50	5.60	54	-1.68
51	5.39	55	-1.65
52	5.11	56	-1.56
53	4.85	57	-1.41
54	4.55	58	-1.29
55	4.19	59	-0.84
56	3.85		
57	3.39		
58	2.90		
60	0.00		

Table 1 – Ordinates of hydrofoil section: NACA4412mod

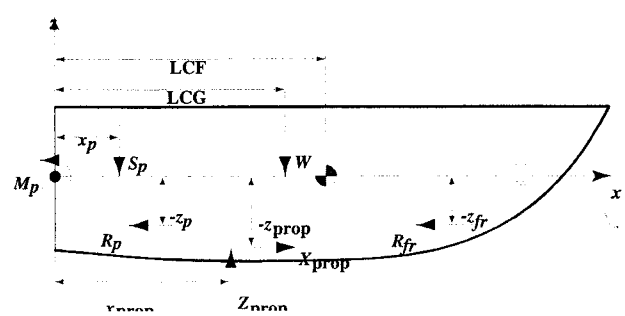

Figure 1 – Location of hull forces in the numerical method.

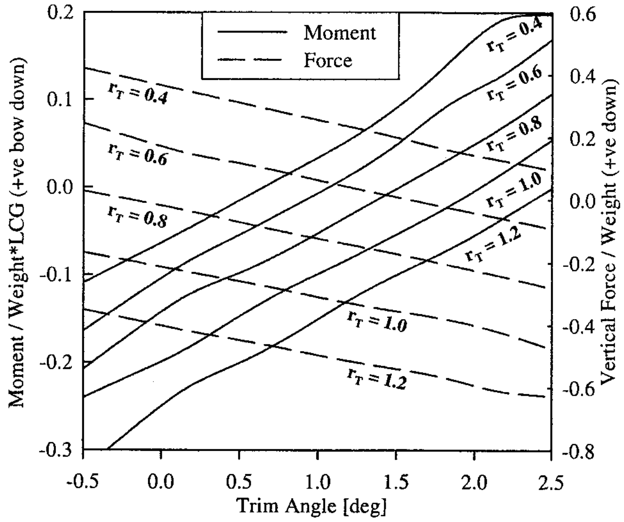

Figure 2 – Values of moment and force plotted against trim and draft.

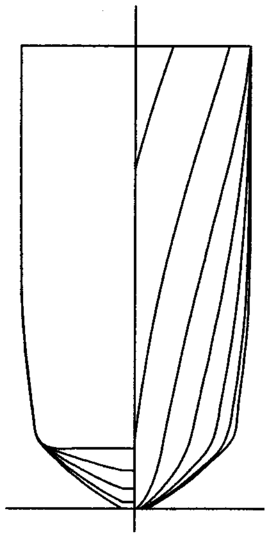

Figure 3 – Body plan of a demihull for the vessel tested.

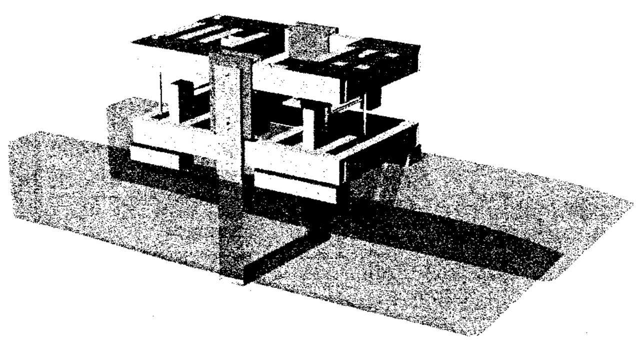

Figure 4 – Setup of the foil-assisted catamaran for experiments with six-component force balance attached.

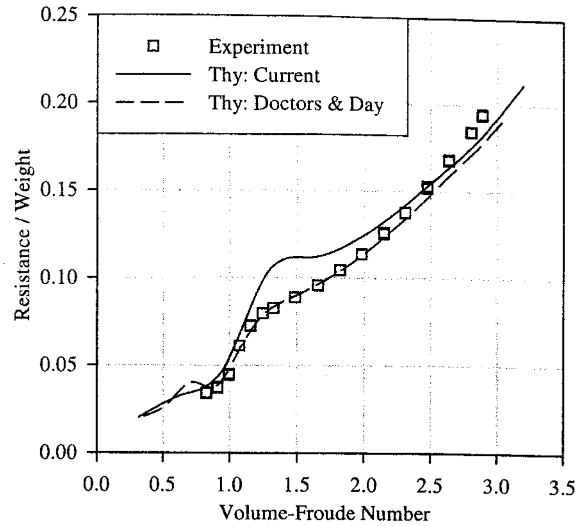

Figure 5 – Resistance data for theory and experiment at 100% of full-load displacement.

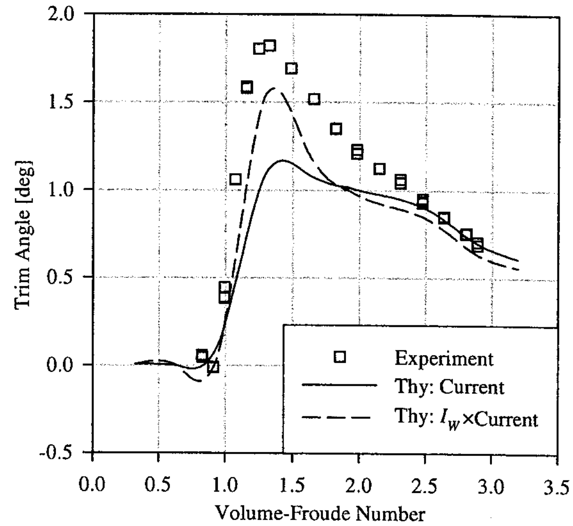

Figure 6 – Trim data for theory and experiment at 100% of full-load displacement.

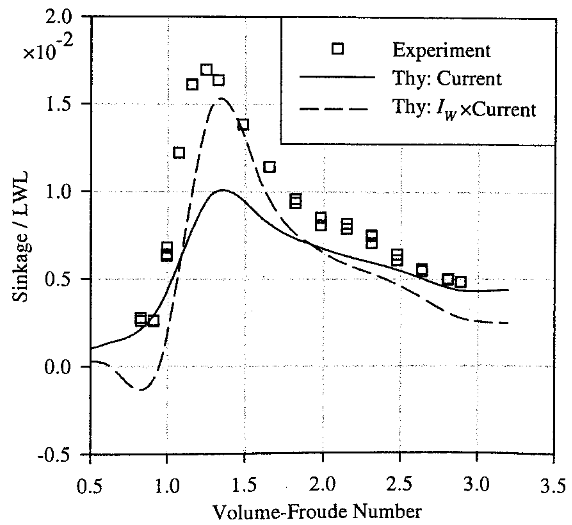

Figure 7 – Sinkage data from theory and experiment at 100% of full-load displacement.

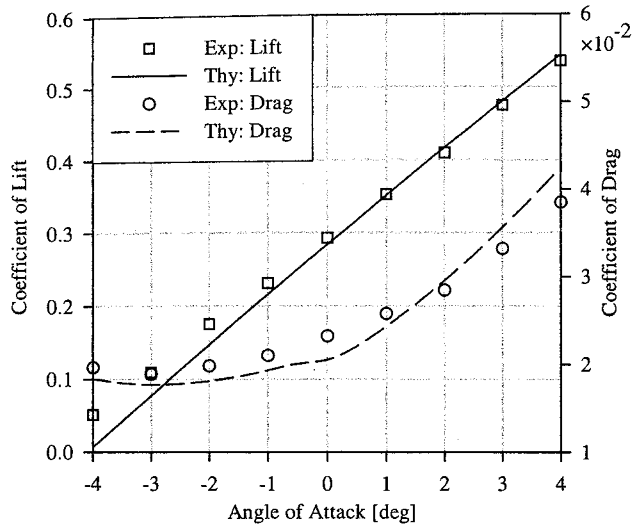

Figure 8 – Comparison of lift and drag coefficients from theory and experiment.

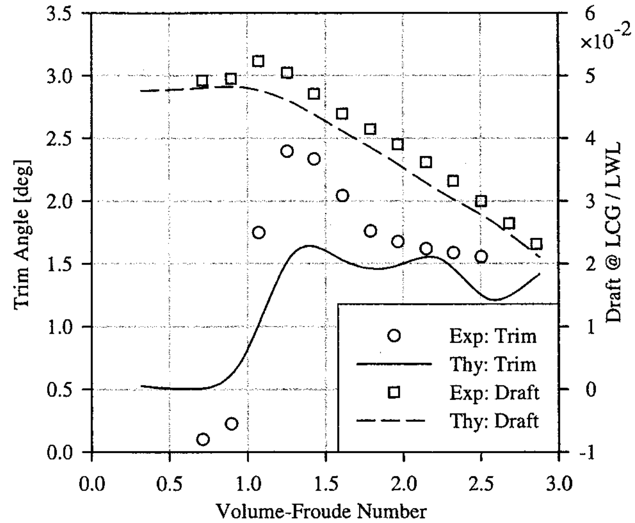

Figure 11 – Comparison of experimental trim and draft with theoretical predictions for a FAC.

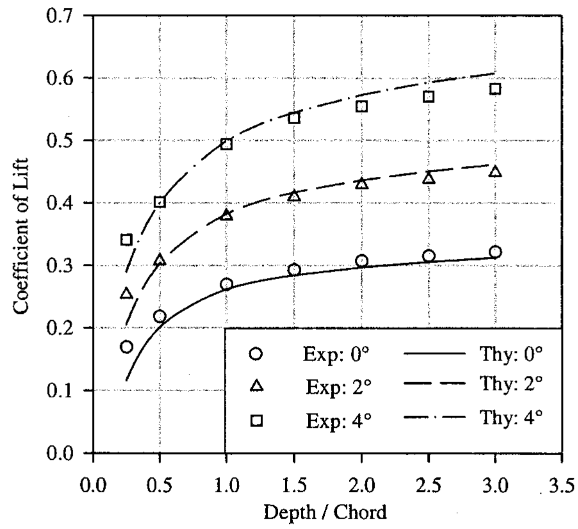

Figure 9 – Comparison of lift versus depth of submergence for theory and experiment at various angles of attack.

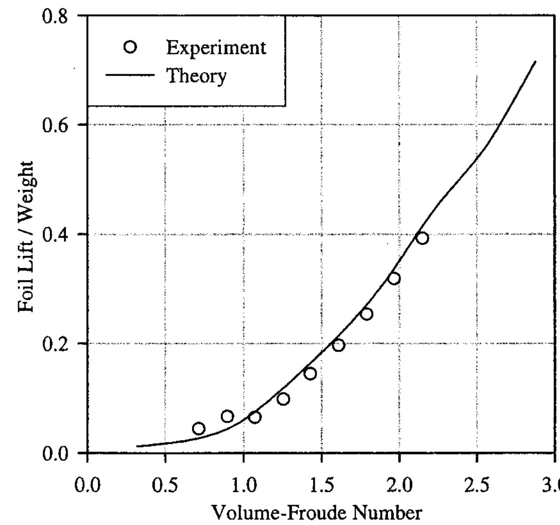

Figure 12 – Comparison of the theory and experiment for foil lift of a foil-assisted catamaran.

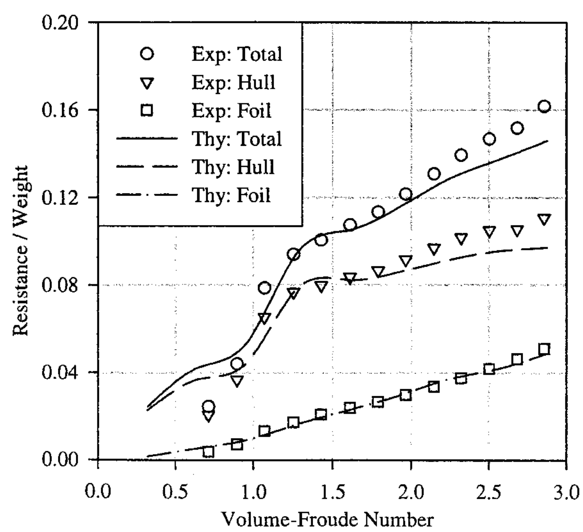

Figure 10 – Comparison of components of experimental drag and theoretical drag prediction for a FAC.

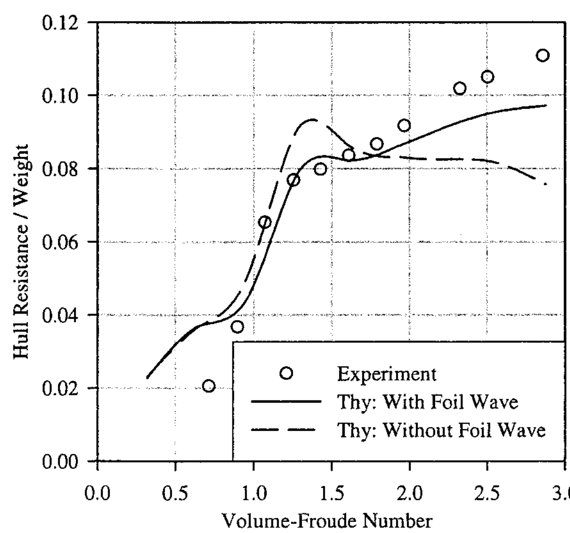

Figure 13 – Comparison of hull drag with and without foil-wave interaction effect.