RESISTANCE EXPERIMENTS ON A SYSTEMATIC SERIES OF HIGH SPEED DISPLACEMENT CATAMARAN FORMS: VARIATION OF LENGTH-DISPLACEMENT RATIO AND BREADTH-DRAUGHT RATIO

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Read in Southampton at a meeting of The Royal Institution of Naval Architects on November 14, 1995, Mr P J Usher, CBE, DSc, FEng, RCNC (President) in the Chair

SUMMARY

The paper summarises an experimental investigation into the resistance components in calm water of high speed displacement catamarans with symmetric demihulls. The experimental programme was a development and extension of earlier work in which a small series of three catamaran models were tested.

Total resistance, running trim, sinkage and wave pattern analysis based on multiple longitudinal cut techniques were carried out for ten round bilge hulls derived from the NPL series. The tests were conducted over a Froude Number range of 0.2 to 1.0 and separation to length ratios of 0.2, 0.3, 0.4, 0.5 and infinity. Interference effects for both the residuary and viscous resistance components were derived.

The results of the investigation provide a better understanding of the components of catamaran resistance including the influence of hull separation, length:displacement ratio and length:beam ratio over a wide range of Froude Numbers. Conclusions are drawn from the results of the hull interference effects on resistance, and practical applications of the results are described.

1. INTRODUCTION

The commercial applications of high speed displacement catamarans has increased significantly over the past few years. Little information is, however, available for carrying out powering estimates for such vessels, particularly in the high speed range.

Work on the resistance of high speed displacement catamarans has been ongoing over a number of years at the University of Southampton (Refs. I and 2) in an effort to improve the understanding of their resistance components and to provide design data. Other published experimental work on such vessels is limited, but includes that reported in Refs. 3 to 6.

This paper describes an extensive series of model tests on catamarans in calm water. The experimental programme is a development of the earlier work (Refs. 1 and 2) in which a small series of three catamaran models were tested. The current work has extended the parametric investigation to cover changes in Breadth:Draught ratio (B/T) and a wider range of Length:Displacement ratios ($L/\nabla^{1/3}$). As in the earlier work, an approach comprising total resistance measurements together with wave pattern analysis was utilised. A wide range of hull separations was tested and, overall, the experiments covered over 40 model configurations, each over a speed range up to a Froude Number of unity. Comprehensive tabulations and plottings of all the test data are given in Ref. 7.

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2 DESCRIPTION OF MODELS

Details of the models used in the investigation are given in TABLE I. The models were built from high density polyurethane foam using an NC cutting machine. This manufacturing technique was able to produce models to a good level of accuracy at relatively low cost.

Models 3b, 4b and 5b had already been tested some three years earlier and their results published in Ref. 2 were they are designated C3, C4 and C5. The results for these models are included in the present paper for comparison and discussion since they form the basis from which the current wider series of models was developed. Some re-tests were carried out on Model 4b to confirm and validate the current test procedure. Also, some element of doubt about the earlier results for Model 5b led to the re-test of that model in mono-hull mode and confirmation of the results for the catamaran modes.

The models were of round bilge form with transom sterns, Fig 1, and were derived from the NPL round bilge series (Ref. 2). This hull broadly represents the underwater form of a number of catamarans in service or currently under construction. The models were firstly tested as monohulls and, in the catamaran configurations, with Separation:Length ratios (S/L) of 0.2, 0.3, 0.4 and 0.5.

The model towing force was in the horizontal direction. The towing point in all cases was situated at the longitudinal centre of gravity and at an effective height one third of the draught above the keel. The models were fitted with turbulence stimulation comprising trip studs of 3.2mm diameter and 2.5mm height at a spacing of 25mm. The studs were situated 37.5mm aft of the stem. No underwater appendages were attached to the models. For some of the smaller displacement models it was necessary to apply a counter balance. Care was taken with its application whereby the effect on accuracy was negligible.

3 FACILITIES AND TESTS

3.1 GENERAL

All the model experiments were carried out in the Southampton Institute of Higher Education test tank which has the following principal particulars:

Length	:	60.0m
Breadth	:	3.7m
Water Depth	:	1.85m
Maximum Carriage Speed	:	4.6 ms^{-1}

The tank has a manned carriage which is equipped with a dynamometer for measuring model total resistance together with various computer and instrumentation facilities for automated data acquisition.

Calm water total resistance, running trim, sinkage and wave pattern analysis experiments were carried out for all the models. All tests were carried out where possible over a speed range up to a little over Fn=1.0. Over the Froude Number range 0.1 to 1.0 the corresponding Reynolds Number (Rn) range for the models was 0.5 x 10^6 to 5.5 x 10^6.

3.2 WAVE PATTERN RESISTANCE

A wave pattern analysis based on multiple longitudinal cuts was applied to all the models. The analysis system was fully automated and consisted of four resistance wave probes, a microcomputer based data acquisition system and data analysis which enabled wave pattern analysis and resistance determination during standard resistance tests.

All wave probes were located at an optimum longitudinal position for longest possible wave traces, whilst transverse positions were chosen to obtain a suitable cosine term in the wave series for every harmonic. This had an important effect on the stability of the analysis which enabled the results to be effectively independent of the transverse positioning of the probes. The analysis method was based on a combined matrix solution of four longitudinal wave traces. The method accounted for short wave traces without truncation errors. A full description of the apparatus and analysis method is given in Ref. 1.

3.3 TRIM AND SINKAGE MEASUREMENTS

Trim and sinkage were monitored for all the tests. Trim (positive bow up) was measured by means of a potentiometer mounted on the tow fitting; accuracy of the measurement was within ±0.05°. Sinkage (positive downwards) was measured by means of a linear displacement potentiometer with a measurement accuracy within ±0.1mm.

3.4 BOW DOWN/TRANSOM EMERGED TESTS

A test case was carried out to derive the form factor for one of the models by running the model bow down with transom emerged. This technique was, for example, mentioned in the discussion to Ref. 2. It has a number of limitations, but a short investigation into its potential uses was considered worthwhile.

4 DATA REDUCTION AND CORRECTIONS

All resistance data were reduced to coefficient form using fresh water density (ρ = 1000 kg/m^3), model speed (v) and static wetted surface area (A) noting that the sum of the wetted areas of both demihulls was used in the case of the catamarans.

$$\text{Resistance Coefficient} = \text{Resistance} / \tfrac{1}{2}\rho A V^2$$

The total resistance measurements were corrected to a standard temperature of 15°C. Corrections due to the drag and influence of the turbulence studs were applied. Tank blockage and shallow water effects were estimated using slender body theory. These were found to be negligible below Fn=0.60 and of the order of 4% of total resistance at Fn=0.95, rising rapidly as the shallow water critical speed was approached. However, there is no evidence of the predicted resistance increase due to shallow water in the experimental data and corrections were not applied. More detailed accounts of these corrections, and the justification for using static wetted area are given in Ref. 7.

5 PRESENTATION OF DATA

The basic presentation of the experimental data adopted in the earlier work (Ref. 2) was as follows:

$$C_{T_{cat}} = (1 + \beta k)C_F + \tau C_W \qquad (1)$$

where:

C_F is obtained from the ITTC-1957 correlation line.

C_W is the wave resistance coefficient for the demihull in isolation.

(1+k) is the form factor for the demihull in isolation.

β is a viscous interference factor.

τ is the wave resistance interference factor.

It is noted that for the demihull in isolation, β = 1 and τ = 1.

Examples of the measured experimental data are presented in Figs 2 to 5. In these diagrams the wave pattern resistance C_{WP} is plotted downward from the total resistance C_T, in the form $(C_T - C_{WP})$. The estimates of $(1 + k)$ or $(1 + \beta k)$ are also shown in the diagrams, these lines being set to the lower envelope of the $(C_T - C_{WP})$ curves when they settle at an approximately constant level above the ITTC friction line at higher Froude Numbers. The values of $(1 + k)$ for the monohulls and $(1 + \beta k)$ for the catamarans are, for practical design purposes, assumed to remain constant over the speed range.

From a practical viewpoint it is not necessary to confine the user to the particular values of $(1 + k)$ or $(1 + \beta k)$ derived in this work. Following the earlier work some concern was expressed over their magnitudes and application, for example see discussion to Ref. 2. For these reasons, residuary resistance coefficients C_R (derived from $C_T - C_{F_{ITTC}}$) have been calculated from the experimental data. These are presented in Figs 6 to 21 and are tabulated in TABLE II. This presentation provides the data in a form suitable for practical powering applications and an overall comparison of the residuary components for the various hull configurations. The user is able to choose a suitable $(1 + k)$ or $(1 + \beta k)$ from this work or other sources. For an estimate of the ship total resistance coefficient it can be shown that, for monohulls:

$$C_{T_{ship}} = C_{F_{ship}} + C_{R_{model}} - k(C_{F_{model}} - C_{F_{ship}}) \qquad (2)$$

and for catamarans:

$$C_{T_{ship}} = C_{F_{ship}} + C_{R_{model}} - \beta k(C_{F_{model}} - C_{F_{ship}}) \qquad (3)$$

It should be noted that model C_T and C_W values can be recovered from the presented data as follows:

for the monohulls:

$$C_T = C_F + C_R$$

$$C_W = C_T - (1 + k)C_F = C_R - kC_F$$

for the catamarans:

$$C_T = C_F + C_R$$

$$C_W = C_T - (1 + \beta k)C_F = C_R - \beta kC_F$$

Use of these equations requires a knowledge of model C_F. Based on the model length of 1.6m and a kinematic viscosity for fresh water of 1.14 x 10^{-6} it can be shown that:

$$C_{F_{model}} = \frac{0.075}{[\log_{10}(Fn \times 5.56 \times 10^6) - 2]^2} \qquad (4)$$

Form and viscous interference factors derived from the investigation in the manner described above are given in TABLE II.

Results of the bow down slow speed tests are given in Fig 22.

Examples of the results of the trim and sinkage measurements are presented in Figs 23 to 26.

6 DISCUSSION OF RESULTS

6.1 TOTAL RESISTANCE AND WAVE PATTERN RESISTANCE

As mentioned in Section 2, representative models from the earlier experimental programme were re-tested in order to confirm and validate the current test procedure. Monohull Model 4b and catamaran Models 4b with S/L=0.3 were re-tested. In both cases the total resistance values showed good agreement with the earlier results. The wave pattern resistance values were in acceptable agreement, showing levels of scatter expected for this component. These tests on the same models were carried out more that three years apart and satisfactorily demonstrated the repeatability of the results and the experimental procedure.

Figures 2 to 5 show examples of the experimental results for the monohull and catamaran tests. It is to be noted that the results from the earlier tests of monohull Model 5b showed some inconsistencies when compared with the current tests. This model was therefore re-tested. The results for C_T were about 5% higher than the original results, and the updated data are used in this paper (see Fig 2).

Examples of the results of the wave pattern measurements are included in Figs 2 to 5 and are plotted downwards from the total resistance values. The results display a hump (or decrease in measured wave pattern resistance) at a Froude Number of about 0.4 before settling down at an approximately constant level above the ITTC correlation line at higher Froude Numbers. Observations during the tests indicate that the large hump is due primarily to transom stern and wave breaking effects in this speed range when the transom is just about to run clear.

6.2 RESIDUARY RESISTANCE; EFFECT OF HULL PARAMETERS

The experimental results are presented in terms of residuary resistance coefficient C_R in Figs 6 to 21, where the residuary coefficient has been derived from $C_T - C_{F_{ITTC}}$. As discussed in Section 5, this presentation is used in order to provide a readily available tool for powering purposes and a means of comparing the relative merits of changes in the hull form parameters.

6.2.1 Monohulls

Examples of the residuary resistance coefficients for the monohulls are shown in Figs 6 and 7 and results for all the models are included in Figs 8 to 17.

The results in Fig 6, for fixed B/T = 2.0, clearly show the influence of Length:Displacement ratio as it is increased from Model 3b to 6b. With increase in Length:Displacement ratio the main resistance hump becomes less pronounced and the Froude Number at which it occurs decreases slightly.

Figure 7 shows the influence of B/T 1.5, 2.0, 2.5) at one Length:Displacement ratio. The influence of B/T is seen mainly in the lower Froude Number range up to about 0.6, and differences between the results of up to 10% due to changes in B/T can occur in this region. In the highest Froude Number range, speeds often representing service speeds for this type of hull form, Model 'c' with the highest B/T = 2.5 tends to have the higher resistance coefficient; the differences between it and the lower B/T ratios tend to be of the order of 3% to 4%. These orders of difference were however not apparent for the higher Length:Displacement ratios. In general the curves tend to cross and recross and no consistent trends are apparent. A similar lack of trend is also found in the Series 64 data (Ref. 9).

6.2.2 Catamarans

Figures 8 to 17 give the results for each of the catamaran models for changes in S/L. The monohull is also shown on each Figure. The general trend in all cases is that as the hull separation is increased, the resistance decreases and the main resistance hump occurs at decreasing Froude Numbers. It is noted that, in the higher speed range, changes in hull separation tend to have a relatively small effect. There is however an increase in residuary resistance for the catamaran compared with the monohull, and this increase becomes a larger proportion of the monohull residuary resistance as Length:Displacement ratio increases from Models 3 to Models 6.

Figures 18 to 21 show comparisons for changes in Length:Displacement and B/T ratios for an S/L value of 0.3. The results for a fixed B/T = 2.0 (Fig 18) show the same general trend as those displayed by the monohulls, with resistance decreasing as Length:Displacement ratio is increased. The results for fixed Length:Displacement ratio and changes in B/T show various trends (Figs 19 to 21). For the highest Length:Displacement ratio (Models 6a -- 6c), Model 6a with the smallest B/T tends to have the largest resistance coefficient. For the low Length:Displacement ratio (Models 4a -- 4c) the trend has been reversed and Model 4a (with the smallest B/T) tends to have the lower resistance coefficient over much of the Froude Number range beyond the resistance hump speed.

6.3 VISCOUS RESISTANCE AND FORM FACTORS

6.3.1 General

Form factors (1 + k) for the monohulls and form factors for the catamarans including viscous interference (1 + βk) were obtained by deducting the wave pattern resistance from the total resistance as described in Section 5.

The resulting values of (1 + k) and (1 + βk) for the various configurations are summarised in TABLE III. As discussed in Section 5, these factors may not necessarily be used directly for design or resistance scaling purposes, but they do provide a broad indication of changes in viscous resistance and viscous interference due to changes in Length:Displacement, B/T and S/L ratios.

6.3.2 Monohulls

For the monohulls, reference to TABLE III indicates a decrease in (1 + k) with increasing Length:Displacement ratio (Models 3 to 6). This was determined by Insel (Ref. 2), and would be expected physically. For each Length:Displacement ratio there is however an insignificant change in (1 + k) with change in *B/T* ratio. The monohull form factors were somewhat higher than might be expected for such vessels. They were of the same order as those found for a similar vessel tested by Tanaka et al (Ref. 10) although much higher than those found by Cordier et al (Ref. 11).

6.3.3. Catamarans

For the catamarans, reference to TABLE III indicates (1 + βk) values to be higher than the corresponding monohull (1 + k) values, indicating β > 1 and suggesting some viscous interference between the hulls as well as the form effect of the demihulls. Part of this increase could be negated by the increase in wave breaking between the hulls at some speeds in the case of the catamarans leading to decreased values of C_{WP} and subsequent overestimates of (1 + βk). Observations at the time of the tests suggest that, in most cases, this effect should not be significant.

As was seen in the earlier tests (Ref. 2), changes in (1 + βk) due to *S/L* are small and do not show a regular trend. There is seen to be a general trend for a slight decrease in (1 + βk) between models 'a' to 'c' (as *B/T* increases from 1.5 to 2.5); this effect is more pronounced at the lower *S/L* ratios. These trends are not fully what might have been expected physically. Whilst the decrease in (1 + βk) with increasing *B/T* might follow from an increasing wave pattern resistance with increasing *B/T*, some increase in viscous resistance might have been expected due to the greater acceleration of the flow through the tunnel. However there is a corresponding decrease in draught with increasing beam.

These results do, however, have implications for the choice of basic hull parameters since they indicate, for a given *S/L*, some reduction in wave interference and wave resistance with decrease in *B/T*, particularly with lower Length:Displacement ratios.

It should be noted however that there is an increase in wetted area for the lowest *B/T* form which could reduce some of this gain, and that at higher speeds the wave pattern resistance is the smaller portion of the total resistance.

6.3.4 Bow Down / Transom Emerged Tests

The results of the bow down / transom emerged tests at low speed for catamaran Model 4a at *S/L* = 0.5 are shown in Fig 22. The results with the transom immersed (normal trim condition) are much more erratic than with the transom emerged. This is likely to be due to the highly turbulent, chaotic wake and vortex / eddy shedding caused by the deeply immersed transom.

The slow speed tests indicate a (1 + βk) value of 1.55 for the normal trimmed condition and 1.37 for the transom emerged case. Prohaska's method was also applied to these particular data and similar values for (1 + βk) were found. TABLE III (where all the (1 + βk) values have been obtained by the (C_T - C_{WP} method) indicates a value of 1.44 for this model.

These results tend to confirm earlier deductions that viscous form and interaction effects are present, although they may be smaller than the values suggested by the (C_T - C_{WP}) method.

Taken overall, and compared with the normal trim condition, the (1 + βk) value derived from the bow down / transom emerged tests was in broad agreement with the value obtained from the wave pattern analysis. In both cases the transom was running clear, indicating that when the transom is immersed and not releasing it has a substantial effect on the flow resulting in an increase in resistance.

It is finally noted that the slow speed bow down / transom emerged tests should be treated with caution due partly to the low resistance forces measured at low speed and the fact that the forward trimmed hull form will be different (although not necessarily significantly) from the actual normal trimmed condition.

6.4 RUNNING TRIM AND SINKAGE

The interference effects on the running trim and sinkage, for a *B/T* of 2.0, can be seen in Figs 23 to 26. The overall results and trends are in broad agreement with published monohull data such as Lahtiharju (Ref. 12) and Tanaka et al (Ref. 10).

In all cases, trim angle interference is important between Fn = 0.3 and Fn= 0.7 where the catamaran displays significantly higher trim angles than the monohull, but generally approaches the monohull trim angle as *S/L* is increased. It was found that as Length:Displacement ratio is increased (when going from Models 3 to 6) there is a decrease in running trim. As *B/T* is increased for a given Length:Displacement ratio (when going from Models 'a' to 'c') the changes in running trim are relatively small.

In general, as Length:Displacement ratio is increased (when going from Models 3 to 6) there is a decrease in running sinkage. It was found that as *B/T* is increased for a given Length:Displacement ratio (when going from Models 'a' to 'c') there tends to be an increase in sinkage or lift effects for the fuller models, particularly at higher speeds.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 The results of the investigation provide further insight into the influence of hull parameters on the resistance components of high speed displacement catamarans, and offer a very useful extension to the available resistance data for this vessel type.

7.2 Length:Displacement ratio was found to be the predominant hull parameter, resistance decreasing with increasing Length:Displacement ratio as might be expected for higher speed displacement vessels.

7.3 The effect of *B/T* on resistance was not large. Changes in resistance due to changes in *B/T* were however identified in particular ranges of speed and Length:Displacement ratio which could warrant attention at the hull design stage. In the main, increase in *B/T* ratio led to an increase in resistance in the lower Length:Displacement ratio range and a decrease in resistance at the highest Length:Displacement ratio.

7.4 The catamaran displays significantly higher running trim angles than the monohull, but generally approaches the monohull angle as *S/L* is increased. Changes in running trim due to changes in *B/T* are relatively small.

As *B/T* is increased there is an increase in running sinkage / lift effects for the fuller models, particularly at higher speeds.

7.5 Form factors for the catamarans were consistently higher than the corresponding monohulls, suggesting some viscous interference between the hulls as well as the form effect of the demihulls. The form factors were found to be effectively independent of speed and to be dependent primarily on length:displacement ratio and to a much lesser extent on hull separation and breadth:draught ratio.

7.6 Bow down / transom emerged tests indicated that the viscous form and interference factors may be lower than those derived directly from the total minus wave pattern resistance results. Whilst the total minus wave pattern resistance method provides very useful information on the general changes in wave pattern and viscous resistance, further work is required to justify and confirm the magnitude of the total viscous term.

7.6 Based on observations during the tests a significant presence of spray and wave breaking was not apparent. Any presence of either or both of these components would however lead to a reduction in the derived viscous form factors. Work pertaining specifically to the quantification of the spray and wave breaking components, where present, would form a useful contribution to the full understanding of the resistance breakdown for this hull type and improve the resistance scaling procedure.

ACKNOWLEDGEMENTS

The work described in this report covers part of a research project funded by SERC through MTD Ltd.

NOMENCLATURE

Demihull	One of the hulls which make up the catamaran (in the current investigation all demihulls are symmetrical)
L, L_{BP}	Length on still waterline [m]
A	Static wetted surface area (demihull) [m^2]
B	Demihull maximum beam [m]
T	Demihull draught [m]
S	Separation between catamaran demihull centrelines [m]
∇	Volume of displacement (demihull) [m^3]
v	Velocity [ms^{-1}]
Fn	Froude Number, $[v/\sqrt{gL}]$
Rn	Reynolds Number, [vL/υ]
C_B	Block coefficient
C_P	Prismatic coefficient
C_R	Coefficient of residuary resistance [R_R/½ ρAv^2]
C_T	Coefficient of total resistance [R_T/ ½ ρAv^2]
C_W	Coefficient of wave resistance [R_W/ ½ ρAv^2]
C_{WP}	Coefficient of wave pattern resistance [R_{WP}/ ½ ρAv^2]
C_F	Coefficient of frictional resistance [ITTC-1957 Correlation line]
1+k	Form factor
β	Viscous resistance interference factor
τ	Wave resistance interference factor
g	Acceleration due to gravity [ms^{-2}]
ρ	Density of water [kg/m^3]
υ	Kinematic viscosity of water [m^2s^{-1}]

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TABLE I: Details of the Models

	Model	L[m]	L/B	B/T	$L/\nabla^{1/3}$	C_B	C_P	C_M	A[m²]	LCB [% [illegible]]
*	3b	1.6	7.0	2.0	6.27	0.397	0.693	0.565	0.434	-6.4
	4a	1.6	10.4	1.5	7.40	0.397	0.693	0.565	0.348	-6.4
*	4b	1.6	9.0	2.0	7.41	0.397	0.693	0.565	0.338	-6.4
	4c	1.6	8.0	2.5	7.39	0.397	0.693	0.565	0.340	-6.4
	5a	1.6	12.8	1.5	8.51	0.397	0.693	0.565	0.282	-6.4
*	5b	1.6	11.0	2.0	8.50	0.397	0.693	0.565	0.276	-6.4
	5c	1.6	9.9	2.5	8.49	0.397	0.693	0.565	0.277	-6.4
	6a	1.6	15.1	1.5	9.50	0.397	0.693	0.565	0.240	-6.4
	6b	1.6	13.1	2.0	9.50	0.397	0.693	0.565	0.233	-6.4
	6c	1.6	11.7	2.5	9.50	0.397	0.693	0.565	0.234	-6.4

4,051 6,672
2,447 7,487
2,451 7,265
2,481 7,248
1,615 8,003
1,640 7,752
1,620 7,845
1,161 8,430
1,157 8,261
1,16 8,281

*Tested earlier and reported in Ref.2

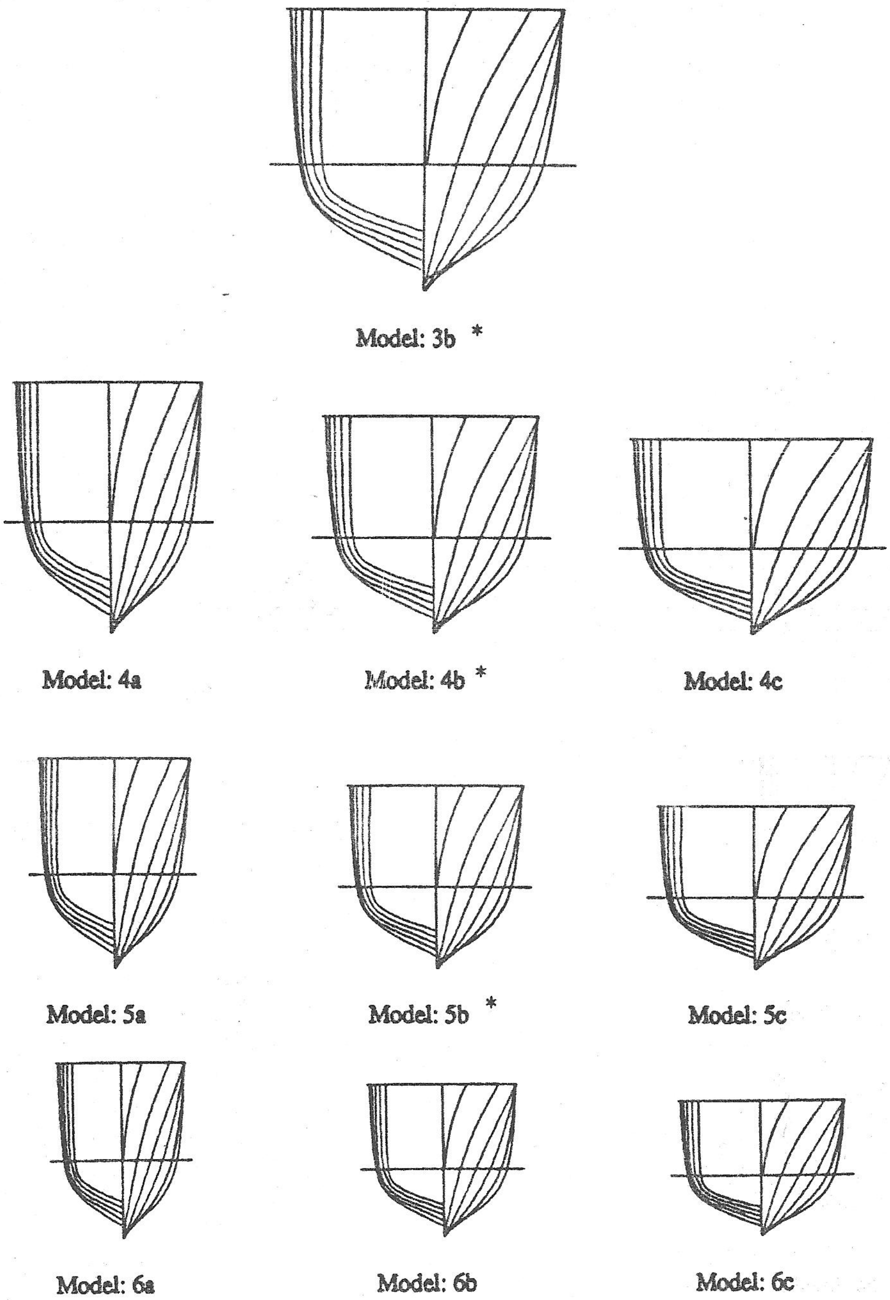

Figure 1: Model Body Plans and Notation

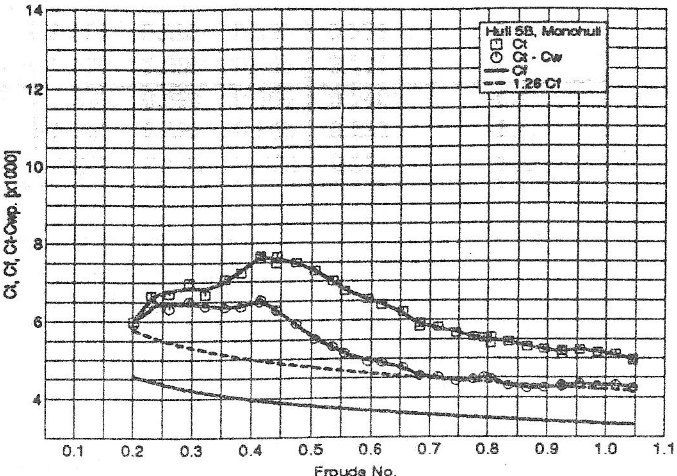

Fig 2. Resistance Components: Model 5b, Monohull

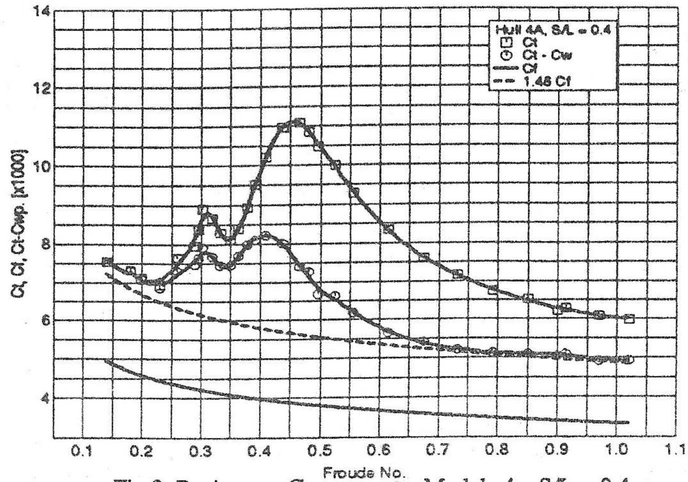

Fig 3. Resistance Components: Models 4a, S/L = 0.4

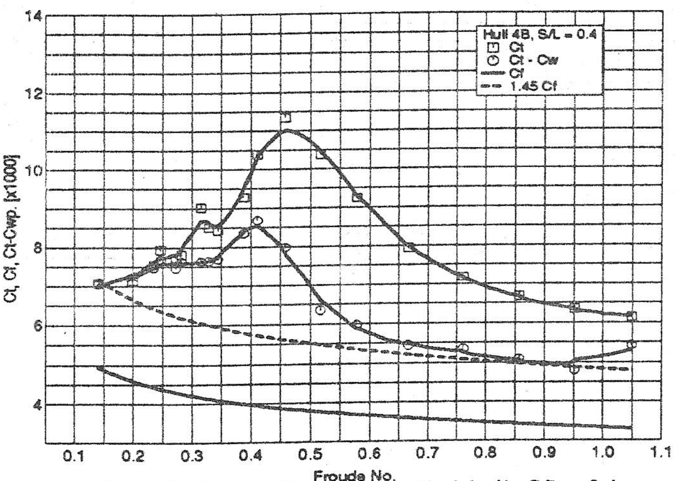

Fig 4. Resistance Components: Models 4b, S/L = 0.4

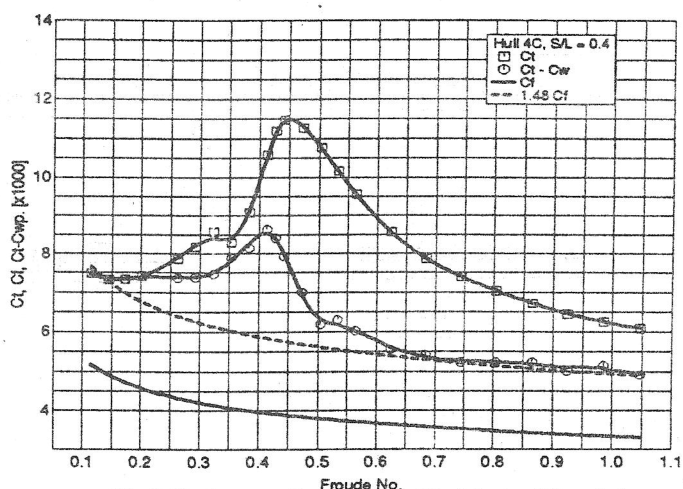

Fig 5. Resistance Components: Models 4c, S/L = 0.4

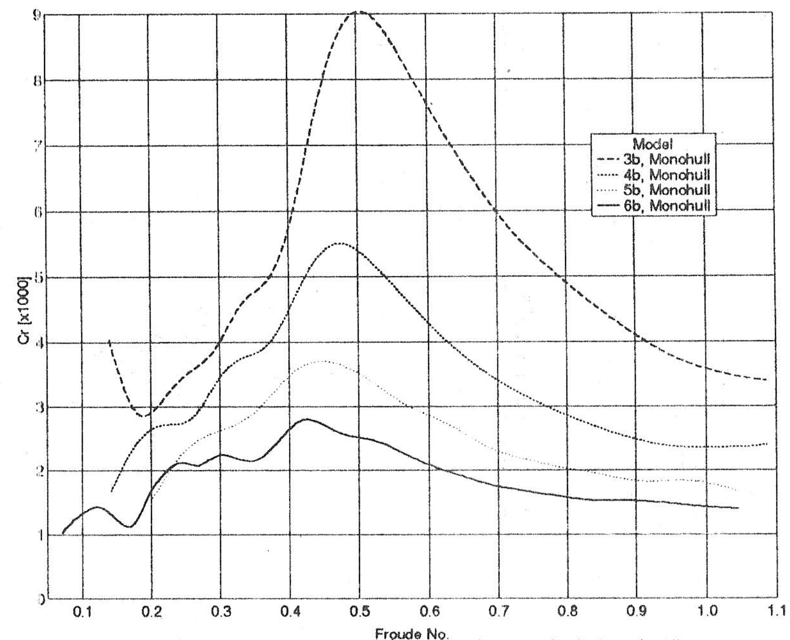

Fig 6. Residuary Resistance: Models: 3b, 4b, 5b, 6b (Monohull)

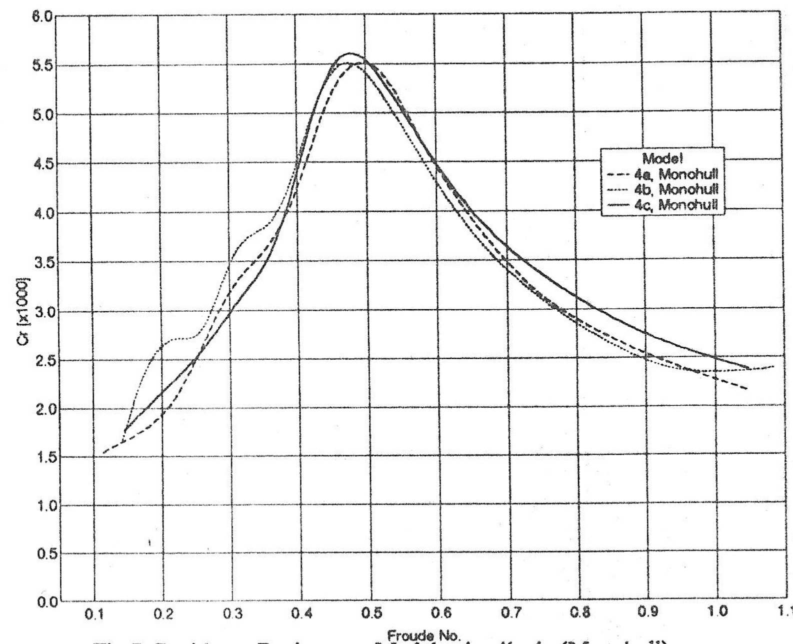

Fig 7. Residuary Resistance: Models: 4a, 4b, 4c (Monohull)

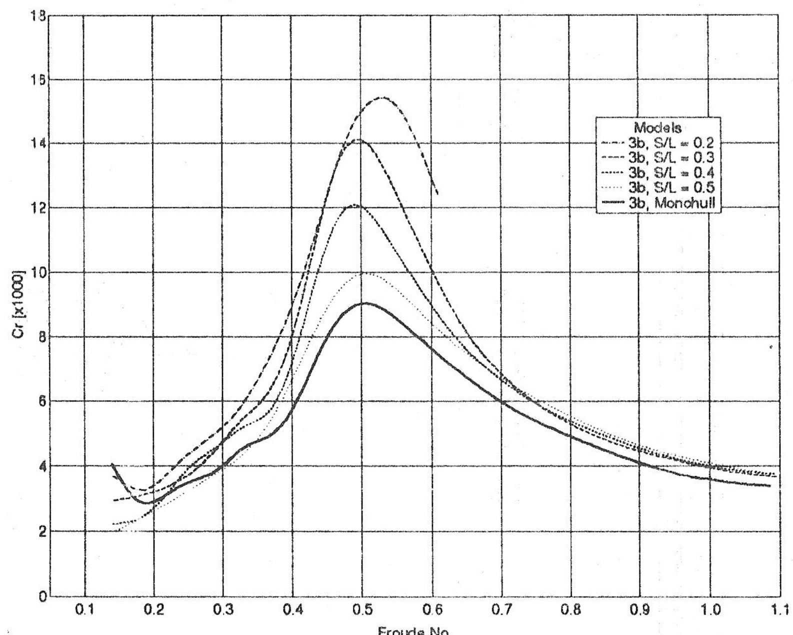

Fig 8. Residuary Resistance: Models: 3b

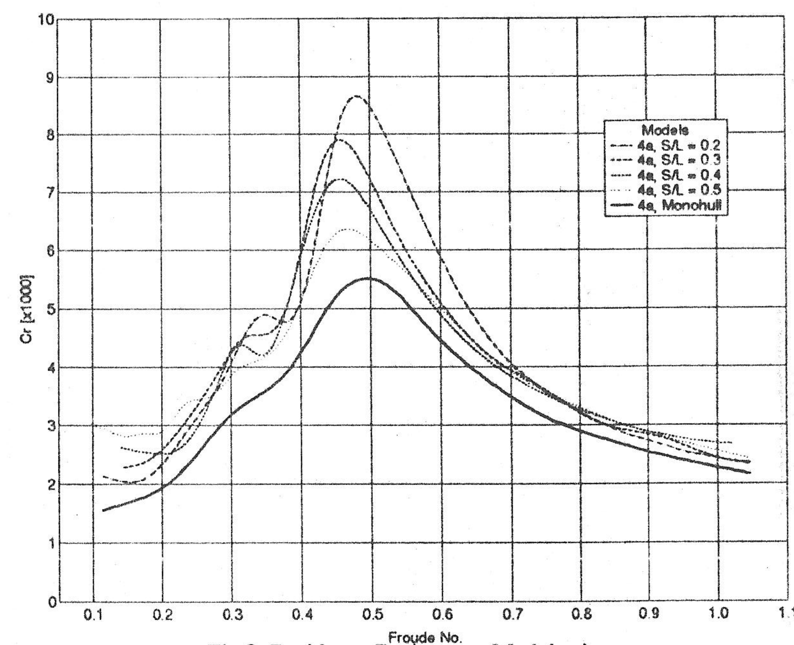

Fig 9. Residuary Resistance: Models: 4a

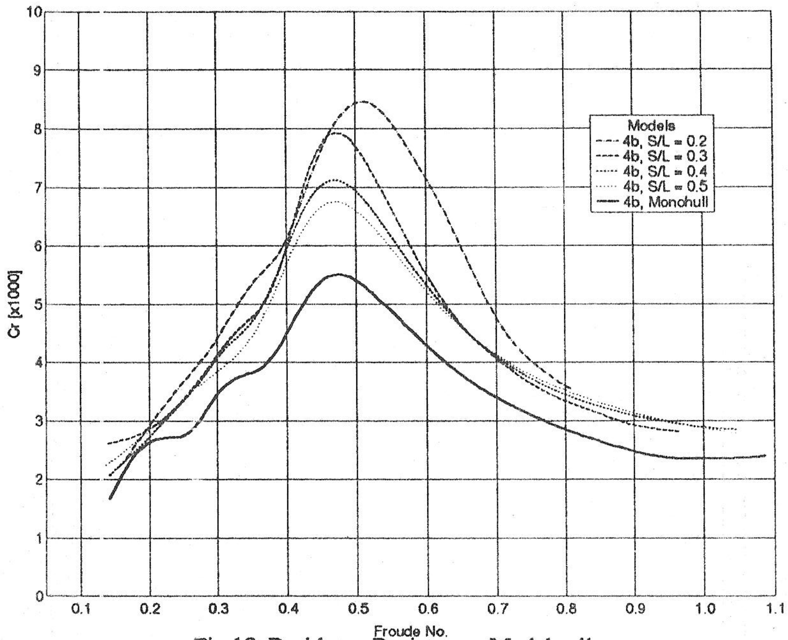

Fig 10. Residuary Resistance: Models: 4b

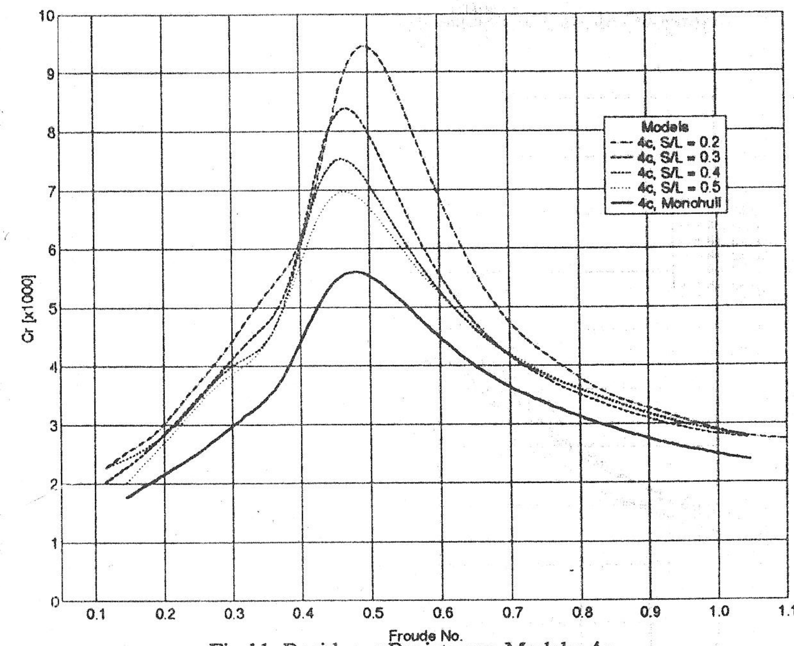

Fig 11. Residuary Resistance: Models: 4c

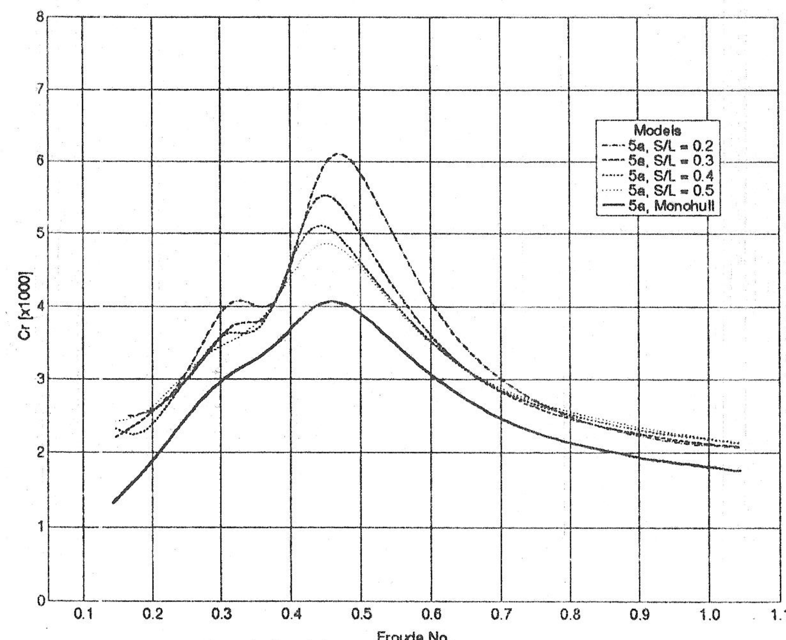

Fig 12. Residuary Resistance: Models: 5a

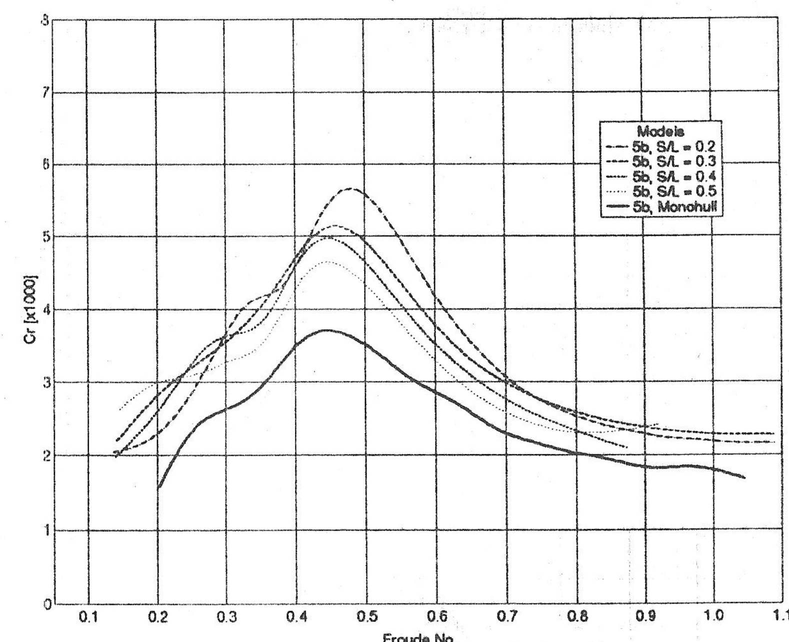

Fig 13. Residuary Resistance: Models: 5b

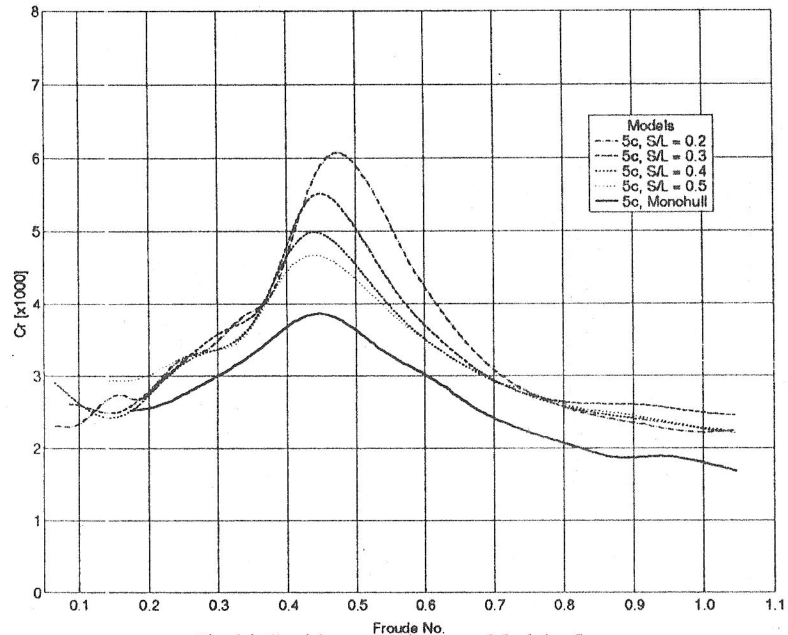

Fig 14. Residuary Resistance: Models: 5c

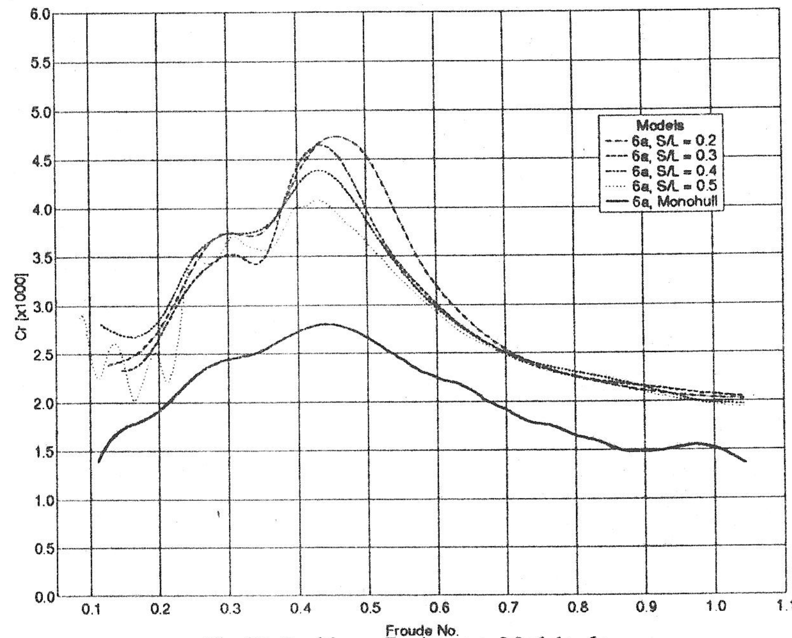

Fig 15. Residuary Resistance: Models: 6a

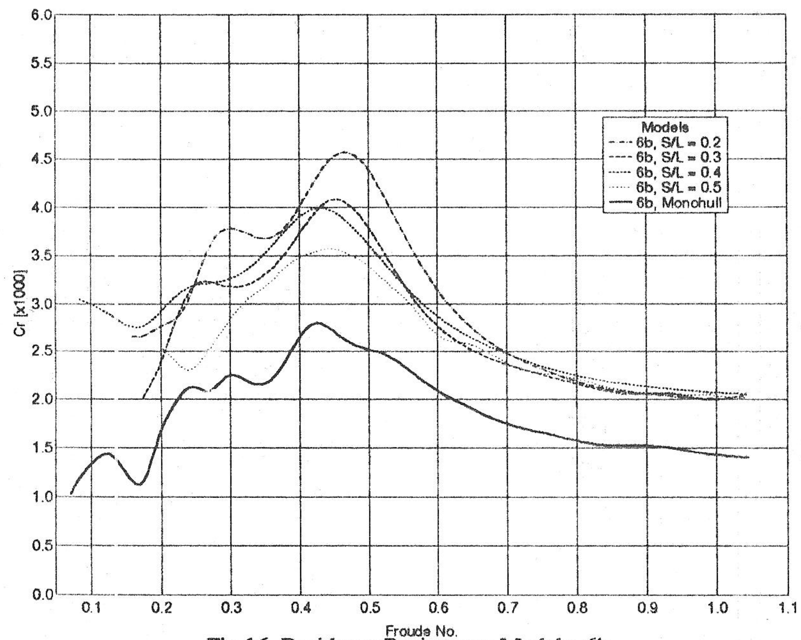

Fig 16. Residuary Resistance: Models: 6b

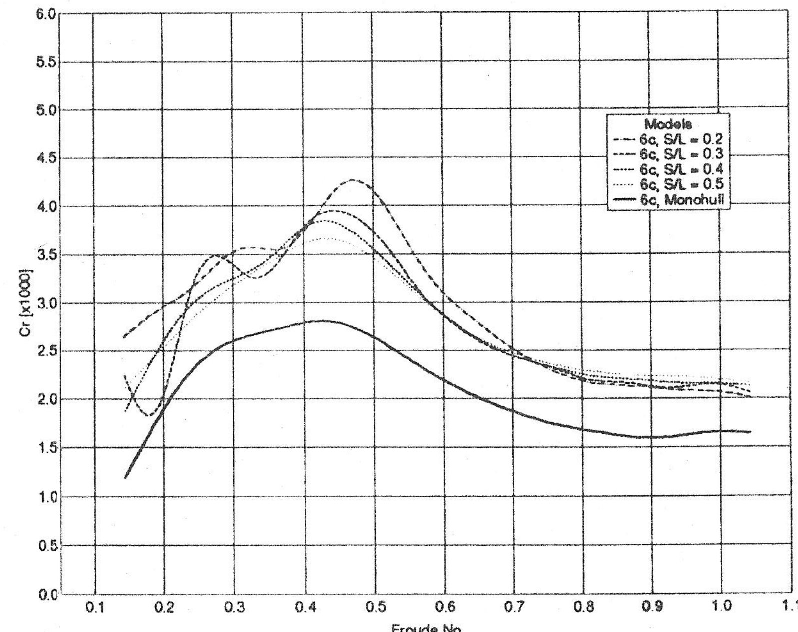

Fig 17. Residuary Resistance: Models: 6c

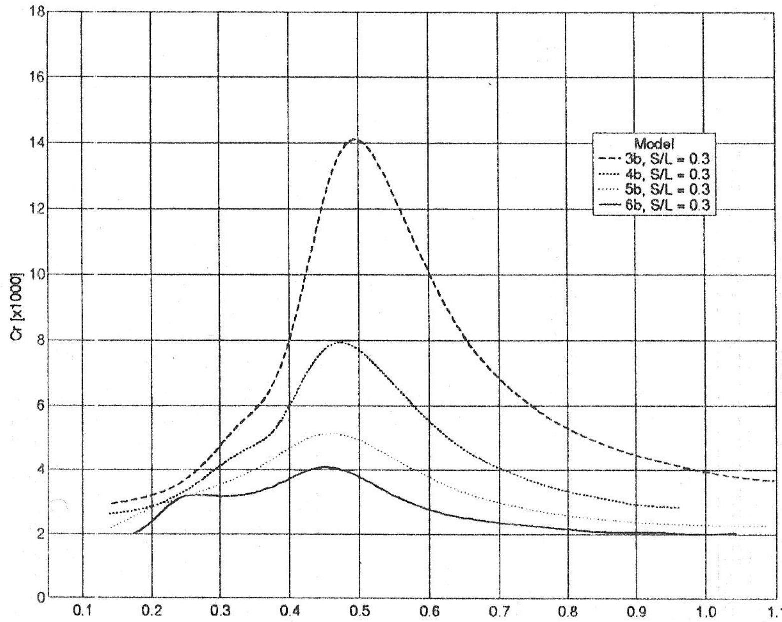

Fig 18. Residuary Resistance: Models: 3b, 4b, 5b, 6b (S/L = 0.3)

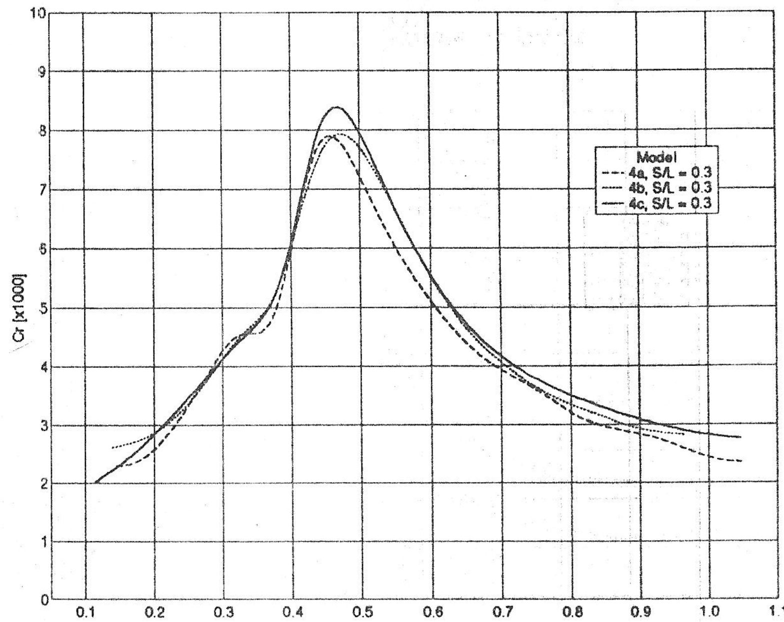

Fig 19. Residuary Resistance: Models: 4a, 4b, 4c (S/L = 0.3)

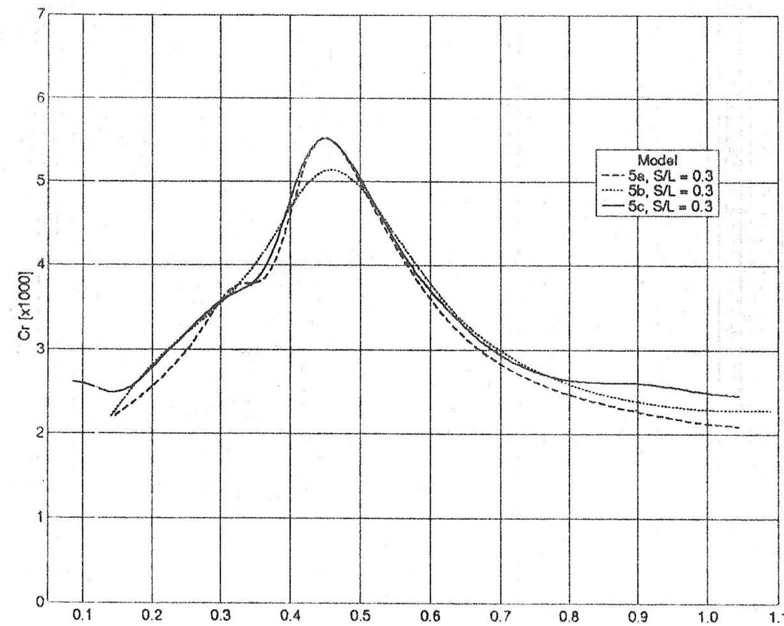

Fig 20. Residuary Resistance: Models: 5a, 5b, 5c (S/L = 0.3)

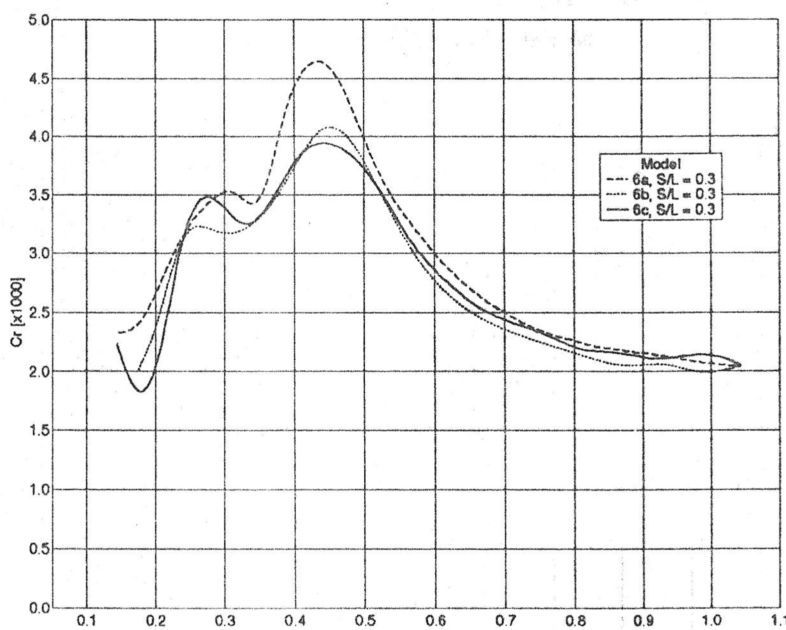

Fig 21. Residuary Resistance: Models: 6a, 6b, 6c (S/L = 0.3)

TABLE II: Model Residuary Resistance Coefficients (Coefficients $\times 10^3$)

TABLE IIa: Model 3b Residuary Resistance ($C_T - C_{F_{ITTC}}$)

Fn	Monohull C_R	S/L = 0.2 C_R	S/L = 0.3 C_R	S/L = 0.4 C_R	S/L = 0.5 C_R
0.200	2.971	3.192	3.214	2.642	2.555
0.250	3.510	4.540	3.726	4.019	3.299
0.300	3.808	5.303	4.750	4.464	3.938
0.350	4.800	6.771	5.943	5.472	4.803
0.400	5.621	8.972	7.648	7.085	6.589
0.450	8.036	12.393	12.569	10.934	9.064
0.500	9.038	14.874	14.237	12.027	10.112
0.550	8.543	15.417	12.275	10.538	9.394
0.600	7.626	12.818	10.089	8.962	8.361
0.650	6.736	8.371	8.123	7.592	7.488
0.700	5.954		6.852	6.642	6.726
0.750	5.383		5.934	5.921	6.078
0.800	4.911		5.289	5.373	5.537
0.850	4.484		4.814	4.949	5.046
0.900	4.102		4.452	4.543	4.624
0.950	3.785		4.172	4.236	4.335
1.000	3.579		3.936	3.996	4.099

TABLE IIb: Model 4a Residuary Resistance ($C_T - C_{F_{ITTC}}$)

Fn	Monohull C_R	S/L = 0.2 C_R	S/L = 0.3 C_R	S/L = 0.4 C_R	S/L = 0.5 C_R
0.200	1.909	2.327	2.564	2.495	2.719
0.250	2.465	3.148	3.315	2.937	3.484
0.300	3.273	3.954	4.283	4.396	3.875
0.350	3.585	5.073	4.576	4.064	4.173
0.400	4.100	4.874	5.871	5.900	5.109
0.450	5.305	8.111	7.953	7.220	6.299
0.500	5.526	8.365	7.150	6.650	6.140
0.550	5.086	7.138	5.990	5.692	5.615
0.600	4.431	5.878	5.090	4.880	4.981
0.650	3.924	4.815	4.392	4.269	4.387
0.700	3.477	4.047	3.949	3.834	3.911
0.750	3.128	3.556	3.594	3.512	3.570
0.800	2.904	3.224	3.187	3.252	3.296
0.850	2.706	2.923	2.966	3.054	3.070
0.900	2.544	2.729	2.839	2.881	2.873
0.950	2.398	2.550	2.657	2.767	2.707
1.000	2.272	2.433	2.437	2.687	2.558

TABLE IIc: Model 4b Residuary Resistance ($C_T - C_{F_{ITTC}}$)

Fn	Monohull C_R	S/L = 0.2 C_R	S/L = 0.3 C_R	S/L = 0.4 C_R	S/L = 0.5 C_R
0.200	2.613	2.929	2.841	2.721	2.820
0.250	2.629	3.686	3.374	3.365	3.396
0.300	3.532	4.311	4.113	4.150	3.902
0.350	3.763	5.483	4.816	4.557	4.329
0.400	4.520	5.897	5.934	5.940	5.716
0.450	5.402	7.748	7.777	7.078	6.741
0.500	5.389	8.420	7.669	6.922	6.581
0.550	4.865	8.099	6.639	6.145	5.921
0.600	4.276	7.159	5.471	5.315	5.209
0.650	3.787	6.008	4.620	4.605	4.593
0.700	3.394	4.769	4.061	4.098	4.125
0.750	3.098	4.041	3.641	3.718	3.786
0.800	2.848	3.605	3.326	3.440	3.520
0.850	2.647		3.153	3.247	3.319
0.900	2.476		2.917	3.078	3.131
0.950	2.361		2.834	2.968	2.998
1.000	2.347			2.882	2.870

TABLE IId: Model 4c Residuary Resistance ($C_T - C_{F_{ITTC}}$)

Fn	Monohull C_R	S/L = 0.2 C_R	S/L = 0.3 C_R	S/L = 0.4 C_R	S/L = 0.5 C_R
0.200	2.169	2.983	2.830	2.801	2.690
0.250	2.506	3.718	3.459	3.412	3.336
0.300	2.987	4.401	4.110	4.067	3.960
0.350	3.349	5.336	4.777	4.321	4.275
0.400	4.371	5.905	5.850	5.919	5.722
0.450	5.525	8.567	8.454	7.605	7.061
0.500	5.512	9.474	7.892	7.013	6.633
0.550	5.021	8.316	6.625	6.087	5.907
0.600	4.473	6.845	5.522	5.249	5.204
0.650	3.995	5.584	4.720	4.617	4.637
0.700	3.632	4.718	4.167	4.165	4.203
0.750	3.360	4.216	3.785	3.845	3.871
0.800	3.119	3.784	3.503	3.587	3.608
0.850	2.922	3.459	3.276	3.364	3.387
0.900	2.743	3.276	3.089	3.165	3.190
0.950	2.603	3.076	2.934	3.003	3.017
1.000	2.481	2.904	2.821	2.875	2.875

TABLE IIe: Model 5a Residuary Resistance ($C_T - C_{F_{ITTC}}$)

Fn	Monohull C_R	S/L = 0.2 C_R	S/L = 0.3 C_R	S/L = 0.4 C_R	S/L = 0.5 C_R
0.200	1.862	2.565	2.565	2.381	2.592
0.250	2.485	3.074	2.991	3.031	3.123
0.300	3.009	3.959	3.589	3.686	3.473
0.350	3.260	4.018	3.756	3.589	3.716
0.400	3.677	4.472	4.604	4.616	4.403
0.450	4.103	6.068	5.563	5.099	4.929
0.500	3.884	5.805	4.950	4.581	4.501
0.550	3.442	4.914	4.221	4.015	3.966
0.600	3.063	4.065	3.596	3.516	3.499
0.650	2.736	3.429	3.138	3.126	3.140
0.700	2.461	3.004	2.827	2.845	2.882
0.750	2.278	2.705	2.615	2.658	2.699
0.800	2.138	2.494	2.465	2.519	2.559
0.850	2.038	2.342	2.351	2.406	2.453
0.900	1.931	2.231	2.260	2.308	2.354
0.950	1.871	2.153	2.183	2.238	2.272
1.000	1.818	2.100	2.124	2.179	2.201

TABLE IIf: Model 5b Residuary Resistance ($C_T - C_{F_{ITTC}}$)

Fn	Monohull C_R	S/L = 0.2 C_R	S/L = 0.3 C_R	S/L = 0.4 C_R	S/L = 0.5 C_R
0.200	1.406	2.288	2.849	2.538	3.006
0.250	2.362	2.843	3.200	3.260	3.093
0.300	2.632	3.643	3.539	3.693	3.330
0.350	2.890	4.194	3.952	3.711	3.437
0.400	3.514	4.520	4.687	4.622	4.303
0.450	3.691	5.506	5.218	4.960	4.648
0.500	3.518	5.581	4.903	4.632	4.324
0.550	3.125	4.927	4.323	4.057	3.804
0.600	2.851	4.177	3.783	3.504	3.286
0.650	2.599	3.555	3.302	3.090	2.872
0.700	2.285	3.051	2.989	2.759	2.576
0.750	2.155	2.744	2.752	2.515	2.396
0.800	2.010	2.529	2.584	2.327	2.310
0.850	1.938	2.383	2.462	2.163	2.322
0.900	1.830	2.298	2.375	2.111	2.382
0.950	1.852	2.221	2.324	2.128	1.852
1.000	1.803	2.186	2.279	2.145	1.803

TABLE IIg: Model 5c Residuary Resistance ($C_T - C_{F_{ITTC}}$)

Fn	Monohull C_R	S/L = 0.2 C_R	S/L = 0.3 C_R	S/L = 0.4 C_R	S/L = 0.5 C_R
0.200	2.517	2.731	2.801	2.718	2.983
0.250	2.756	3.256	3.199	3.203	3.290
0.300	3.010	3.445	3.599	3.386	3.371
0.350	3.273	3.937	3.779	3.623	3.625
0.400	3.687	4.635	4.813	4.731	4.519
0.450	3.891	5.908	5.543	4.969	4.644
0.500	3.621	5.864	5.016	4.513	4.340
0.550	3.232	5.095	4.274	3.945	3.855
0.600	3.048	4.231	3.703	3.495	3.512
0.650	2.685	3.576	3.267	3.183	3.187
0.700	2.417	3.074	2.930	2.920	2.936
0.750	2.205	2.771	2.741	2.717	2.779
0.800	2.076	2.558	2.632	2.564	2.594
0.850	1.903	2.434	2.607	2.476	2.514
0.900	1.863	2.346	2.599	2.404	2.454
0.950	1.915	2.259	2.550	2.341	2.358
1.000	1.785	2.213	2.481	2.256	2.281

TABLE IIh: Model 6a Residuary Resistance ($C_T - C_{F_{ITTC}}$)

Fn	Monohull C_R	S/L = 0.2 C_R	S/L = 0.3 C_R	S/L = 0.4 C_R	S/L = 0.5 C_R
0.200	1.916	2.727	2.660	2.807	2.484
0.250	2.257	3.379	3.244	3.595	3.515
0.300	2.443	3.792	3.548	3.761	3.665
0.350	2.527	3.665	3.381	3.754	3.566
0.400	2.723	4.377	4.403	4.257	4.009
0.450	2.796	4.703	4.593	4.339	3.998
0.500	2.658	4.592	3.974	3.855	3.635
0.550	2.434	3.799	3.382	3.338	3.243
0.600	2.246	3.193	2.994	2.955	2.916
0.650	2.111	2.812	2.703	2.689	2.651
0.700	1.917	2.534	2.496	2.505	2.475
0.750	1.781	2.367	2.348	2.379	2.336
0.800	1.633	2.253	2.261	2.304	2.243
0.850	1.544	2.176	2.194	2.230	2.171
0.900	1.478	2.110	2.155	2.146	2.093
0.950	1.528	2.062	2.110	2.047	2.021
1.000	1.521	2.027	2.064	1.976	1.962

TABLE Ii: Model 6b Residuary Resistance ($C_T - C_{F_{ITTC}}$)

Fn	Monohull C_R	S/L = 0.2 C_R	S/L = 0.3 C_R	S/L = 0.4 C_R	S/L = 0.5 C_R
0.200	1.755	2.864	2.297	2.933	2.353
0.250	2.136	3.217	3.235	3.203	2.335
0.300	2.255	3.769	3.162	3.251	2.833
0.350	2.150	3.667	3.299	3.502	3.158
0.400	2.639	4.007	3.721	3.913	3.479
0.450	2.696	4.534	4.092	3.950	3.570
0.500	2.510	4.379	3.771	3.592	3.393
0.550	2.338	3.734	3.202	3.196	3.085
0.600	2.084	3.144	2.762	2.866	2.662
0.650	1.900	2.738	2.507	2.635	2.565
0.700	1.747	2.477	2.355	2.468	2.378
0.750	1.656	2.311	2.249	2.339	2.268
0.800	1.575	2.184	2.158	2.241	2.214
0.850	1.527	2.093	2.068	2.172	2.112
0.900	1.523	2.052	2.056	2.129	2.064
0.950	1.482	2.020	2.046	2.089	2.048
1.000	1.426	2.001	2.001	2.063	2.036

TABLE IIj: Model 6c Residuary Resistance ($C_T - C_{F_{ITTC}}$)

Fn	Monohull C_R	S/L = 0.2 C_R	S/L = 0.3 C_R	S/L = 0.4 C_R	S/L = 0.5 C_R
0.200	1.882	2.979	1.909	2.608	2.515
0.250	2.395	3.169	3.328	3.056	2.911
0.300	2.581	3.539	3.401	3.252	3.191
0.350	2.666	3.531	3.309	3.385	3.366
0.400	2.785	3.684	3.774	3.813	3.629
0.450	2.816	4.229	3.932	3.813	3.676
0.500	2.626	4.154	3.719	3.527	3.446
0.550	2.394	3.573	3.256	3.187	3.145
0.600	2.177	3.080	2.855	2.866	2.851
0.650	2.006	2.809	2.595	2.609	2.608
0.700	1.866	2.504	2.437	2.432	2.487
0.750	1.754	2.305	2.331	2.345	2.358
0.800	1.682	2.165	2.199	2.232	2.297
0.850	1.633	2.138	2.167	2.210	2.249
0.900	1.568	2.108	2.120	2.174	2.227
0.950	1.628	2.078	2.121	2.149	2.227
1.000	1.672	2.067	2.134	2.157	2.193

TABLE III: Form Factors from C_{WP} Measurements

$L/\nabla^{\frac{1}{3}}$	B/T	Model:	Monohull $1+k$	S/L = 0.2 $1+\beta k$	β	S/L = 0.3 $1+\beta k$	β	S/L = 0.4 $1+\beta k$	β	S/L = 0.5 $1+\beta k$	β
6.3	2.0	3b	1.45	1.60	1.33	1.65	1.44	1.55	1.22	1.60	1.33
7.4	1.5	4a	1.30	1.43	1.43	1.43	1.43	1.46	1.53	1.44	1.47
7.4	2.0	4b	1.30	1.47	1.57	1.43	1.43	1.45	1.50	1.45	1.50
7.4	2.5	4c	1.30	1.41	1.37	1.39	1.30	1.48	1.60	1.44	1.47
8.5	1.5	5a	1.28	1.44	1.57	1.43	1.54	1.44	1.57	1.47	1.68
8.5	2.0	5b	1.26	1.41	1.58	1.45	1.73	1.40	1.54	1.38	1.46
8.5	2.5	5c	1.26	1.41	1.58	1.43	1.65	1.42	1.62	1.44	1.69
9.5	1.5	6a	1.22	1.48	2.18	1.44	2.00	1.46	2.09	1.48	2.18
9.5	2.0	6b	1.22	1.42	1.91	1.40	1.82	1.47	2.14	1.44	2.00
9.5	2.5	6c	1.23	1.40	1.74	1.40	1.74	1.45	1.96	1.44	1.91

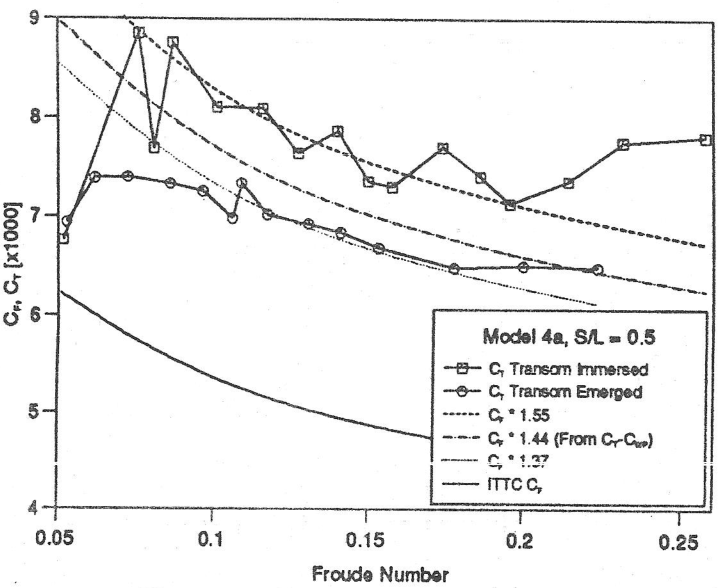

Fig.22 Form Factor from SlowSpeed Tests

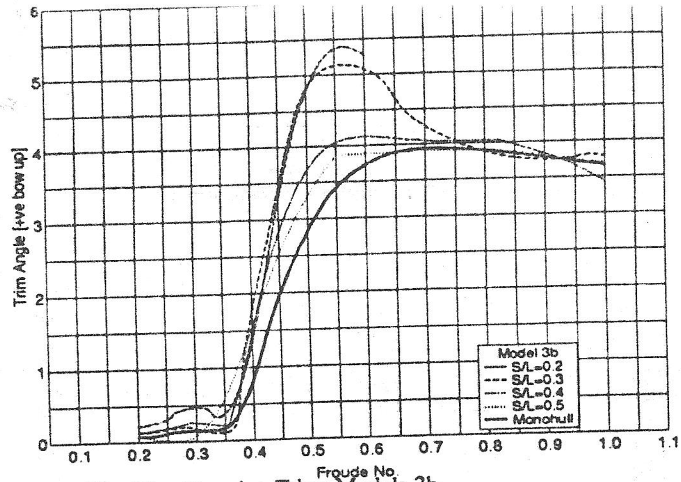

Fig.23a. Running Trim: Models 3b

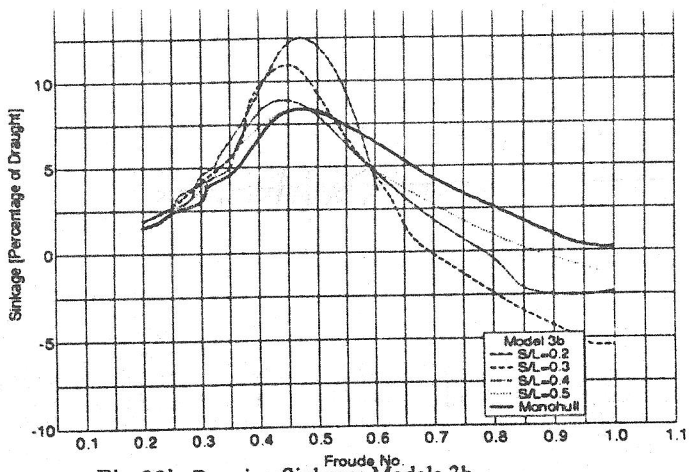

Fig.23b Running Sinkage: Models 3b

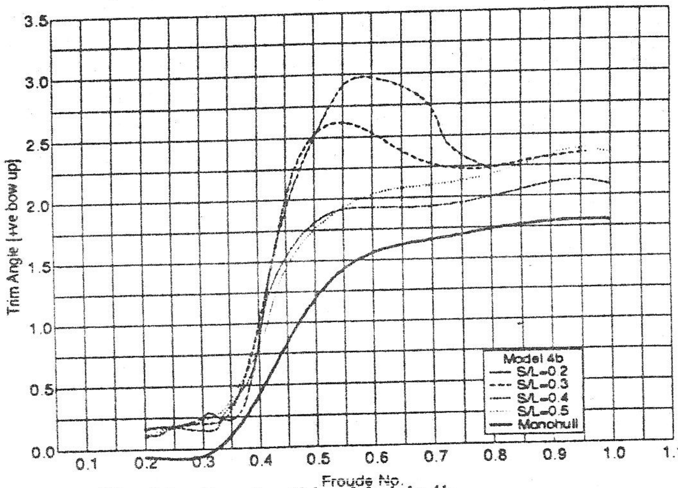

Fig.24a Running Trim: Models 4b

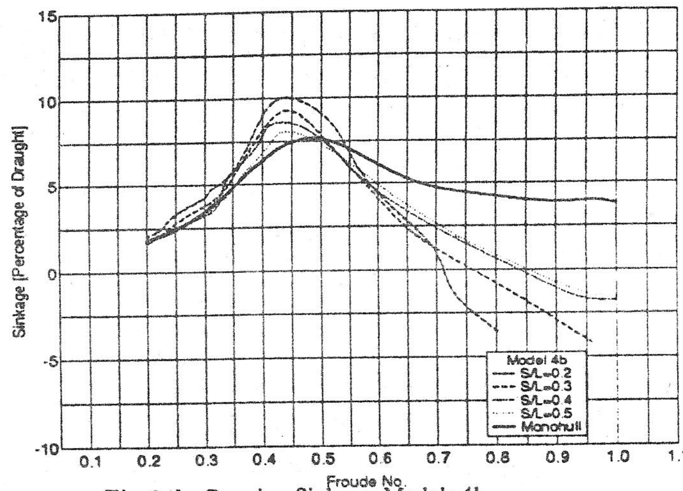

Fig.24b. Running Sinkage: Models 4b

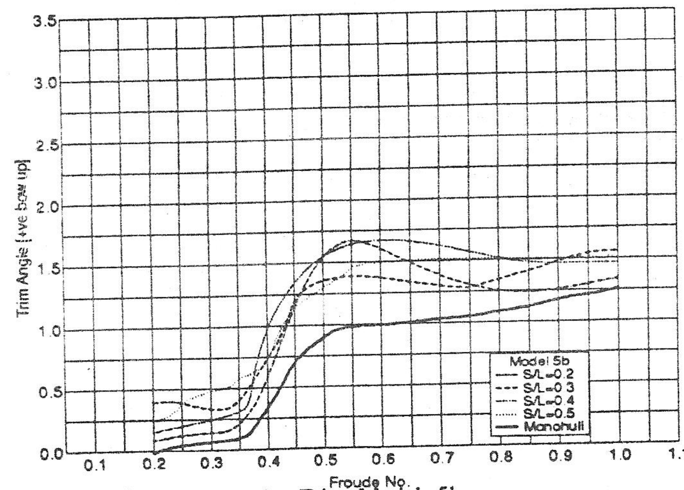

Fig.25a. Running Trim: Models 5b

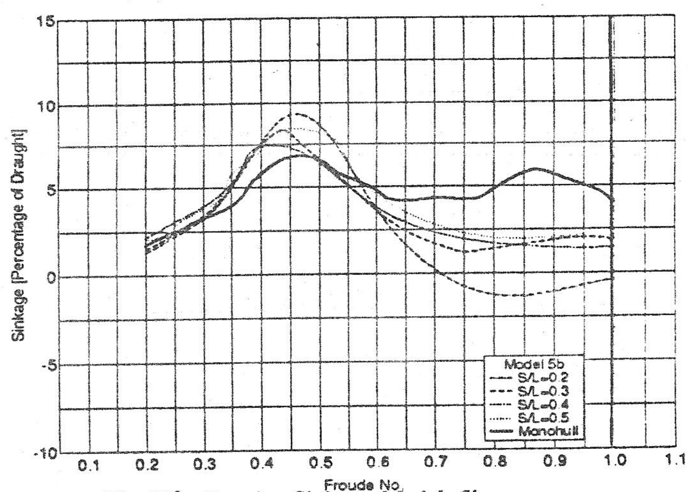

Fig.25b. Running Sinkage: Models 5b

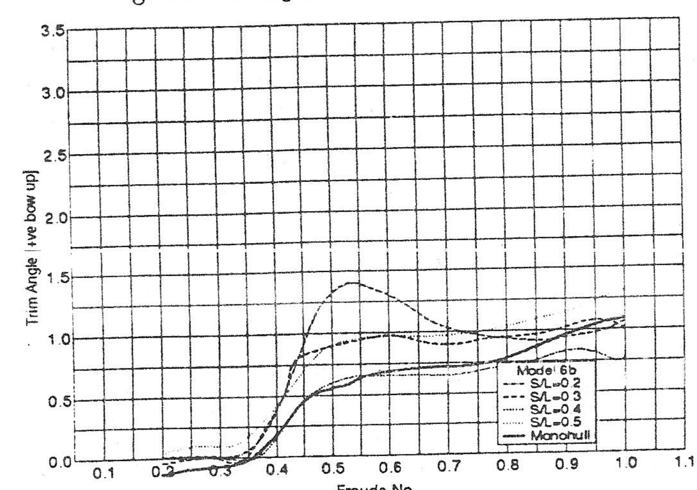

Fig.26a. Running Trim: Models 6b

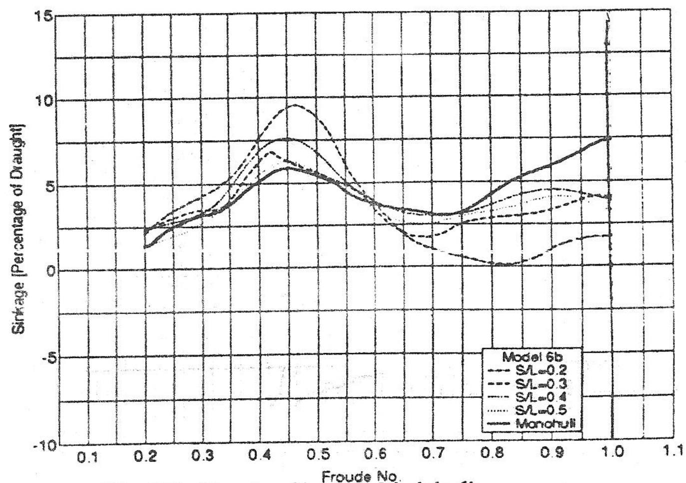

Fig.26b Running Sinkage: Models 6b

DISCUSSION

Mr N I Gee, BSc(Hons) (Fellow): May I thank the authors for not only producing this excellent paper, but also for publishing a full set of systematic data for catamaran forms in an extremely useful range of geometries and Froude Numbers. There is far too little systematic data published on this subject and this paper will, I am sure, become a standard reference point for those wishing to investigate the effect of changes of geometry on catamaran forms. Of particular interest is that this series is derived from the NPL round bilge series and therefore, the monohull data presented forms of valuable extension to the David Bailey series at higher length displacement ratios.

Secondly, I have a question concerning the published results. It is well recognised that demi-hull spacing has a profound effect on catamaran resistance, particularly at Froude Numbers in the region of 0.5. However, many modern high speed catamaran designs are operating at Froude Numbers of the order of 1.0 where hull spacing has far less effect on resistance. There are many hundreds of catamarans operating with hull lengths of approximately 35 metres at speeds of between 33 and 36 knots, therefore having a characteristic Froude Number of approximately 1.0.

Figures 9,12 and 15 conveniently show collected curves of residuary resistance coefficient for the hull forms having low beam/draught ratio and length/displacement ratios of 7.4, 8.5 and 9.5 respectively. The curves allow direct comparison between monohulls and catamarans with varying hull spacing. As expected, the curves show that hull spacing has very little effect at a Froude Number of 1.0 or (presumably) at higher Froude Numbers. However, although small variations in resistance with varying spacing are apparent, there is no indication that the results for catamarans at high demi-hull spacings are approaching those for the monohull, even though it must be the case that at infinite spacing the C_R values for the catamaran must be identical with those for the monohull. Indeed, the results in Figures 12 and 15, in particular, indicate that the catamaran curves are converging on a limiting value which is significantly in excess of the value for monohulls.

It is also surprising that the difference between the lowest catamaran C_R value and the comparable monohull value is some 10% for models 4a (length/displacement ratio 7.4) increasing steadily to some 33% for models 6a (length/displacement ratio 9.5). This suggests that the interference effects between the catamaran hulls even at a high value of spacing/length is greater for hulls having high length/displacement ratios than for those with a lower ratio. It would surely be expected that the higher length/displacement ratio (slenderer) forms would experience less interference effect than those with low length displacement ratios.

Is it possible that some of these differences between catamaran and monohull resistance coefficients are due to the method of analysis which uses a constant static wetted surface area throughout. Catamaran residuary resistance coefficients may be artificially high because of a greater wetted surface area caused by interference from the bow wave trials. Whilst this would account for the catamaran curves never fully converging with the monohull curves, it would still not explain the greater difference for the slenderer forms.

It may be interesting to note that our own recent tank experiments with a catamaran model having parameters very close to model 5a and spacing/length ratio of approximately 0.3 yielded a C_R value of approximately 1.5×10^{-3} using corrected values for wetted surface area.

Mr K R Suhrbier, Dr.-Ing. (Fellow): I thank the authors for their paper providing additional information to their earlier work. Research on the hydrodynamic characteristics of multihull craft is certainly timely. I welcome the presentation of the monohull and catamaran residuary coefficients C_R derived on the basis of the 1957 ITTC Correlation Line.

Having been involved in powering and model - full scale extrapolation problems, also within ITTC activities, my attention was inevitably drawn to the form factors (the ratio of the viscous resistance coefficient of the 3-dimensional hull to that of the corresponding 2-dimensional formulation (or plate)) presented in Table III. Form factors have been the subject of investigations and discussions for several decades, but the progress made so far is still not very satisfactory. Any further work should therefore be welcome.

Accepting the authors' comments in Section 6.3.1 and 6.3.2, I would like to make the following remarks: The values obtained (by a total minus wave pattern resistance approach) are rather higher than might be expected. Taking, for instance, the figure for the monohull model 3b, i.e. $1+k = 1.45$, and considering that some form effect is already included in the 1957 ITTC formulation, this result means that the viscous resistance for this hull would be about 50% higher than that of a flat plate.

Hull forms rather similar to model 3b have been used for several vessels built and tested on trials. As stated in an earlier contribution, the application of the above factor (or similar) would have resulted in an underprediction of power of about 10% (Suhrbier Discussion to Ref. 2).

Although some viscous form effects must exist on practically all types of ship hulls, including those of fast craft, the ITTC High-Speed-Marine Vehicles and the Powering Performance Committee of the 19th ITTC (Ref. 13) recommended (or stayed with) the use of $k = 0$, thus ignoring viscous form effects; the HSMV Committee though, allowed for $k \neq 0$ if determined by special investigations.

Recent investigations by Cordier and Dumez (Ref. 11), also referred to in this paper, included experiments with larger models of a semi displacement type monohull (3.2m and 6.2m). Form factors closer to unity (or somewhat below) were derived, rather than the much higher values determined by Tanaka et al (Ref. 10), based on Hughes' approach, with small models of the same hull form. Interestingly, they also derived a significant wave breaking component (as was conjectured by several contributors to the discussion of Ref. 2). Such a contribution, if confirmed for the series, would of course influence the form factors presented in this paper.

In view of the above and the implications regarding resistance and power predictions for monohulls as well as catamarans, it seems most desirable that further investigations and analyses should be carried out, possibly including CFD analyses, larger scale tests, wind tunnel experiments, etc.

Finally, may I perhaps add that resistance tests with a series of hard chine catamaran models (3.6m to 5.2m) have been conducted at the Berlin Model Basin (Müller-Graf, Ref. 14) within the German high-speed craft R&D programme and that now a regression analysis of these results (for 21 hull variants and 48 combinations of hull parameters) has been published by Zips (Ref. 15).

REFERENCES

13. Proc. 19th Int. Towing Tank Conf., Madrid 1990.

14. MÜLLER-GRAF, B: 'The Scope of the VWS Hard Chine Catamaran Hull Series '89.' FAST '93, Proc. 2nd Int. Conf. on Fast Sea Transportation, Yokohama, 1993.

15. ZIPS, J M: 'Numerical Resistance Prediction Based on the Results of the Hard Chine Catamaran Hull Series '89.' FAST '95, Proc. 3rd Int. Conf. on Fast Sea Transportation, Lübeck-Travemünde, 1995.

Mr D Hinge (Companion): I would like to echo Nigel Gee's thanks to the speakers for their interesting paper. Information like this is not normally published, since it is of commercial value to the naval architect.

With reference to Fig. 3 in particular, I have a question about the subtraction of the wavemaking component from the total resistance. It can be seen that the Ct=Cw curve still shows apparent evidence of the characteristic secondary and primary wavemaking resistance humps. With this in mind, can the authors be sure that their method of calculating Cw is indeed accounting for all of the wavemaking component?

Added Written contribution

Much of our work at Douglas Hinge & Associates is with fully planing vessels which can have problems overcoming the main resistance hump at a Froude number of about 0.5. The problems occur mainly due to the propulsion system, which is geared for say 50 knots, the wavemaking resistance and the large viscous separation resistance around a deeply immersed transom (such vessels needing fairly prismatic aft sections).

If the viscous separation resistance around the transom is affected by the wavemaking pattern, which I would suggest that it is, would it not be of advantage to separate out this component from the rest of the viscous resistance? (It could be argued that part of this separation resistance is a component of the wavemaking resistance, being directly caused by it, but that would blur the distinction between Cw and Cf).

Mr N F Warren, BSc(Hons) (Member): Published results on the resistance of fast catamaran forms are very sparse, so this paper is a very valuable contribution. It whets the appetite for more variations; whereas a good range of L/B, B/T, and $L/\nabla^{1/3}$ and S/L is covered it is only for one basic form with fixed CB Cp Cm and LCB, i.e. the NPL form. Variations can be endless; no doubt the optimum LCB varies with Froude number. The optimum C_B and Cp no doubt varies with Froude number probably in the same manner as a monohull. But for a catamaran the demi-hull shape is free from the constraints of required stability and roll damping. It is likely that the optimum demi-hull shape is not like the NPL form. At the higher Froude numbers and higher values of $L/\nabla^{1/3}$ it is notable what a small proportion of the total resistance is attributable to residuary resistance. It is possible to minimise the wetted area of a demi-hull in a fashion impossible on a monohull, for example, with semi-circular hull sections.

The results of trim and sinkage particularly of the models with a high $L/\nabla^{1/3}$ show how small the effects are. Clearly there is no hydrodynamic lift and one wonders whether the transom, so traditional to modern fast craft, is actually necessary?

On a detailed note could the author confirm the definition of R_R; presumably this is half the total since A is the area of the demi-hull and ∇ is the volume of the demi-hull. Also R_T and R_W; are these half the total? I believe in dealing with catamarans, in order to avoid mistakes of a factor of two, it is always better to talk of TOTALS! Similarly it would be very useful if the data could be presented in a form so that comparisons with the original NPL work and series 64 for example, could be made directly, i.e. residuary resistance plotted as residuary divided by displacement rather than divided by a function of surface area which really has little relationship to wave making resistance.

Dr D K Brighton: The authors are to be congratulated for clarifying what shape catamaran hulls should be. So little data is available. They have tested models around the optimum wetted area/maximum immersed cross-sectional area of 25 (where resistance (friction drag) is similar to form drag (water displacement)). Some clarification may, however, help the lay reader. It is probable that some of the points below have already been included, but taking them in chronological order:

3.2 is wave pattern resistance the same as Froude drag?

5. Can $C_{F\ model}$ numbers (Eqn (4) be explained a little further?

6.1 The transom runs clear at high F_n but is there any evidence of planing or of reduction of wetted area or even of reduction of maximum cross-sectional area immersed? The reduction of total drag at $F_n > 0.5$ seems to follow sinkage (Figs. 23b-26b), which is assumed to be stern sinkage, since a draught of 0.08m 2° up implies a stern depth of ~0.08m and a bow depth ~0.

6.2.1 It is important to note that resistance reduces with increasing length/displacement, but can it be compared against volume displacement (all-up-weight)? Could trim/sinkage be included? A quick check at $F_r = 1$ suggest that C_r varies linearly with weight for all models.

6.2.1 Is displacement = draught + sinkage? Is length the wetted length rather than model length? Is the difference significant? Can the similarity of data between models a-c be attributed to them having similar wetted cross-sectional areas?

Nomenclature - should v be velocity, ν for viscosity throughout? See Para 4. Is B the water-line maximum beam width?

Figs. 23a-26a - are trim angles in Degrees?

Prof. D Bruzzone: I think the authors must be congratulated for this interesting paper in which very useful data are reported in a form directly available for the hydrodynamic design of catamarans. The data herein reported, and especially those in the report form of Ref. 7, may also be useful for validations of computer programs based on methodologies belonging to numerical hydrodynamics. The considered hull form and all its proposed variants are, in fact, readily available and the effects of form variations may be investigated from a theoretical point of view and compared with the proposed data.

Some work was carried out by the discusser (Ref. 16) about the wave resistance of those hull forms using the data of Ref. 7. In this respect it would be very useful to know, even approximately, the Froude number for which the transom gets clear. Could the authors give some information about this point?

REFERENCE

16. BRUZZONE, D and FERRANDO, M: 'Numerical Evaluation of the Steady Free Surface for Catamaran Hull Forms', Symposium on High Speed Marine Vehicles, Naples, April 1995.

AUTHORS' REPLY

Mr Gee comments on operational Froude numbers and that many vessels operate at a Froude number of about 1.0. This is true for the 30m-40m craft but it can also be observed that the more recent breed of larger catamarans in the range 70m-110m are operating at much lower Froude numbers of the order of 0.5-0.6, where, as Mr Gee mentions, hull spacing can have a significant effect on resistance.

The second point raised by Mr Gee concerns the apparent anomaly that even at the higher spacing between the hulls the catamaran curves are still significantly in excess of those for the monohulls. As Mr Gee suggests, the full physical significance is not represented in the curves since in catamaran mode wetted surface area tends to be higher due to the wave system on the inboard sides of the hulls, and this might account for some of the differences between the catamarans and monohulls. We would however expect that at an S/L value of 0.5 some hull interference effects would still exist. It is a fact that, at model scale, the differences between the catamarans and monohulls get larger with increase in length:displacement ratio but the reason is unclear.

Mr Gee gives an example of his own model test results based on running wetted surface area. We would expect an increase in the running wetted area over the static wetted area of the order of 14%-17% for these catamaran forms in the Froude number range 0.8-1.0. It is pleasing to note that the results in the paper, when corrected for this effect, would give a C_R value broadly corresponding to that given by Mr Gee.

Dr Suhrbier raises the subject of form factors for this type of craft and the authors would agree that progress made so far is still not very satisfactory. They would also agree with the cautionary note, implied in Dr Suhrbier's discussion, on the magnitude of the form factors to be used for practical purposes. The authors accept that form factors obtained by the total minus wave pattern resistance approach are higher than might be expected, and this is acknowledged in the paper. We do not at present have a definitive reply for Dr Suhrbier except to say that, like Cordier and Dumez (Ref. 11), we are continuing to investigate what might be termed the deficit or gap in the total resistance budget for these vessel types which might include wavebreaking, spray, transom effects and, in the case of multihulls, induced drag due to hull crossflow and viscous interference effects. These investigations will include further wake traverse experiments with a view to identifying surface debris due to wave breaking and the use of CFD analyses and wind tunnel tests in an attempt to improve the understanding of viscous interference. We would agree with Dr Suhrbier that the use of larger models would be beneficial in elucidating scale effects. The authors also thank Dr Suhrbier for pointing out the published papers on the German high speed craft programme which are now available, Refs. 14 and 15.

Mr Hinge questions the results of subtracting the wave pattern resistance from the total, and the separation of transom effects from the viscous resistance. After several years experience and validation of our wave cut method we are confident that the analysis takes account of all the wave pattern components. The results, such as those in Fig. 3, can be a little misleading since the apparent hump in the Fn range 0.3-0.6 is due primarily to transom stern and wave breaking effects and strictly should not be included in the viscous component. By assuming a constant form factor (whatever its level) this does assume that the resistance within the hump is part of the Froude number dependent residuary or wavemaking resistance. It should however be stressed that the scaling law to be applied to the wavebreaking and transom stern resistance component is not yet known. The same is also true of the large pressure form component, which may not scale directly in proportion to skin friction, although it is conventional to assume that it does so.

Mr Warren makes the interesting suggestion of minimising wetted area using, say, semi-circular hull sections. On the basis that any savings are worth having we would agree. However, recent resistance tests on models having substantial changes in prismatic coefficient (in one case moving towards semi-circular sections) indicate that, assuming a ship shape is to be retained at the ends, then savings of the order of only 2%-3% in wetted area are likely to be achieved.

We would agree that the results would suggest that there is not a need for a transom stern, but suspect that the practicalities of installation of jet propulsion units are likely to lead to the retention of transom sterns along the lines of those currently used.

On the subject of wetted surface area we appreciate the need for clarity in the definition of coefficients in the case of multihulls. In our work we refer to the total resistance and use the sum of the wetted areas of both demi-hulls in the case of the catamaran, as stated in Section 4 of the paper. This does allow direct comparison of the specific resistance coefficients for the monohulls and catamarans.

Mr Warren raises the fundamental issue that a vessel can have varying hull shape, hence wetted area, for the same displacement and that Residuary Resistance/Displacement would be a preferable presentation. We opted to non-dimensionalise using wetted area in order to follow current practice, but fully appreciate the reasons for Mr Warren's suggestion. The alternative presentation can of course be recovered from the data in the paper and, for a fixed length/displacement ratio, would entail multiplying the coefficients by the relevant wetted area x $\frac{1}{2} \rho V^2/\Delta$.

Dr Brighton asks a question concerning resistance components. We would prefer not to use the term 'Froude drag' but the now accepted components of friction, viscous pressure and wave resistance (noting that the total wave resistance is made up of wave pattern resistance and any wave breaking resistance). Other effects such as those due to transom, spray induced drag and viscous interference may also be present, as discussed in our reply to Dr Suhrbier. We suspect Dr Brighton's 'Froude drag' refers to Froude's original residuary resistance as defined in this paper, being derived by subtracting skin friction from total resistance.

Equation 4 is the model C_F using the ITTC formula $C_F = 0.075/(\log Rn-2)^2$ with the Reynolds number Rn for a model size of 1.6m cast in terms of Froude number, whereby

$$Rn_m = Fn \times 5.56 \times 10^6.$$

C_F for ship is derived from the ITTC formula using ship Rn in the usual way.

Dr Brighton comments on transom, sinkage and wetted area effects. The trim and sinkage values are relative to still water. Whilst there is some vertical rise (negative sinkage) at higher speeds, due to the change in wave form over the hull the net wetted area increases by as much as 14%-17% at higher speeds compared with still water, as mentioned in our reply to Mr Gee. Also, the net hydrodynamic contribution to lift is relatively small for these hull types within the speed range considered. Whilst mass displacement does not of course change, it would be unwise to make deductions from draught plus sinkage since this does not take account of the wave form over the hull. The length referred to is the length on the still waterline. The running waterline length shows only small changes with speed for these hull forms. Models a-c have similar cross-sectional areas, but we would not necessarily attribute similarity of resistance data to this. The flow is complex with B/T having an influence on both the wave and viscous interference effects between the hulls. Finally in reply to Dr Brighton we would confirm that V is used for velocity, v for kinematic viscosity (with the earlier errors in the preprint of the paper now corrected), B is the waterline maximum beam and trim angles are in degrees.

The authors would agree with Professor Bruzzone on the use of the experimental results for the validation of theoretical approaches and were pleased to learn that he was able to use some of the data for that purpose. Professor Bruzzone asks when the transom runs clear. We attempted to monitor this condition during our experiments and these suggest that the transom runs clear at Fn = 0.3 to 0.4.

In conclusion, the authors would like to express their thanks to all the discussers for their helpful and stimulating contributions.