AN INVESTIGATION INTO THE RESISTANCE COMPONENTS OF HIGH SPEED DISPLACEMENT CATAMARANS

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SUMMARY: The paper summarises an experimental and theoretical investigation into the resistance components in calm water of high speed displacement and semi-displacement catamarans with symmetric demihulls.

Total resistance, running trim, sinkage experiments and wave pattern analysis based on multiple longitudinal cut techniques were carried out for a mathematically defined hull form (Wigley hull) and three 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. Wake traverse analysis was also carried out for the Wigley model and one round bilge model. Interference effects for both the wave pattern and the viscous resistance components were derived.

A theoretical method based on linearised wave resistance theory was developed, and examples of its application compared with experimental results.

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

1. INTRODUCTION

The demand for high speed small ships has increased during the last two decades, especially in the passenger ferry boat market. Various hull forms have been developed to satisfy the design criteria of these vessels. Among them the catamaran concept has received considerable attention for such applications due to its large deck area, high transverse stability and unusual resistance characteristics.

Catamaran resistance presents a complex problem as the interference effects between the demihulls must be considered in addition to the resistance of the demihulls in isolation. Two types of interference resistance specific to catamarans can be identified, namely, viscous interference caused by the asymmetric flow around the demihulls and its effect on the viscous flow such as boundary layer formation and the development of vortices, and wave interference resistance originating from the interactions between the wave systems of the demihulls.

Although a number of experimental and theoretical investigations of catamaran resistance have been conducted in the past, e.g. Refs. 1, 2, 3, 4, there is a lack of understanding of the interference resistance components, especially at higher speeds. For example, there is effectively no published information available for displacement catamarans at speeds greater than about Fn = 0.5, i.e. the range specifically applicable to modern high speed displacement catamarans.

The present study attempts to improve the understanding of the calm water resistance characteristics of high speed displacement catamarans. An approach comprising total resistance measurements together with wave pattern analysis and wake surveys was utilised. A wide range of hull separations and a speed range up to a Froude Number of unity was covered.

A Wigley hull form was tested which allowed a limited comparison to be made with published data. A series of three round bilge hulls was also tested which allowed the performance of typical catamaran hulls to be investigated and provides some practical catamaran resistance data for use at the preliminary design stage.

2. DESCRIPTION OF MODELS

A survey of built catamarans revealed the main application range of high speed catamaran hull form parameters to be L/B: 6 - 12, $L/\nabla^{1/3}$: 6 - 9, B/T: 1.0 - 3.0 and C_B: 0.33 - 0.45. These parameters were borne in mind when choosing the principal model dimensions.

Details of the models used in the investigation are given in Table I.

The first model (denoted C2) had a parabolic (Wigley) hull form, Fig. 1. This model allowed the test set-up to be validated using published monohull data, Refs. 5 and 6, and limited catamaran data, Ref. 3.

Models C3, C4 and C5 were of round bilge form, Fig. 1, and were derived from the NPL round bilge series, Ref. 7. This hull form broadly represents the form of a number of catamarans in service or currently under construction. Use of this hull form also allowed validation of the monohull data (for the lowest $L/\nabla^{1/3}$ ratio) using the resistance data in Ref. 7.

In the catamaran configurations, separation to length ratios (S/L) of 0.2, 0.3, 0.4 and 0.5 were tested. An example of the models (C5) in catamaran configuration is shown in Fig. 2.

The model towing force was in a horizontal direction. The towing point in all cases was situated at the longitudinal centre of gravity and at an effective height one third of draught above keel. The models were fitted with

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turbulence stimulation comprising trip studs of 3.2mm diameter and 2.5mm height at a spacing of 25mm. The studs were situated 90mm aft of the stem in the case of the Wigley hull (C2) and 37.5mm aft of the stem in the case of the NPL hull forms (C3, C4, C5). No underwater appendages were attached to the models.

TABLE I Details of the Models

MODEL	C2	C3	C4	C5
L(m)	1.800	1.600	1.600	1.600
L/B	10.000	7.000	9.000	11.000
B/T	1.600	2.000	2.000	2.000
$L/\nabla^{1/3}$	7.116	6.273	7.417	8.479
C_B	0.444	0.397	0.397	0.397
C_P	0.667	0.693	0.693	0.693
C_M	0.667	0.565	0.565	0.565
$A(m^2)$	0.482	0.434	0.338	0.276
LCB(%L ⊗)	⊗	-6.4	-6.4	-6.4
MATERIAL	GRP	FOAM	FOAM	FOAM
HULL	PARABOLIC	ROUND BILGE	ROUND BILGE	ROUND BILGE

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 m/s

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 0.5×10^6 to 5.5×10^6. Wake traverse analysis was carried out at a limited number of speeds for the Wigley model (C2) and one round bilge model (C3).

3.2 Wave Pattern Resistance

A wave pattern analysis based on multiple longitudinal cuts was developed and applied to all the models. It is a fully automated acquisition - analysis system consisting of four resistance wave probes, a

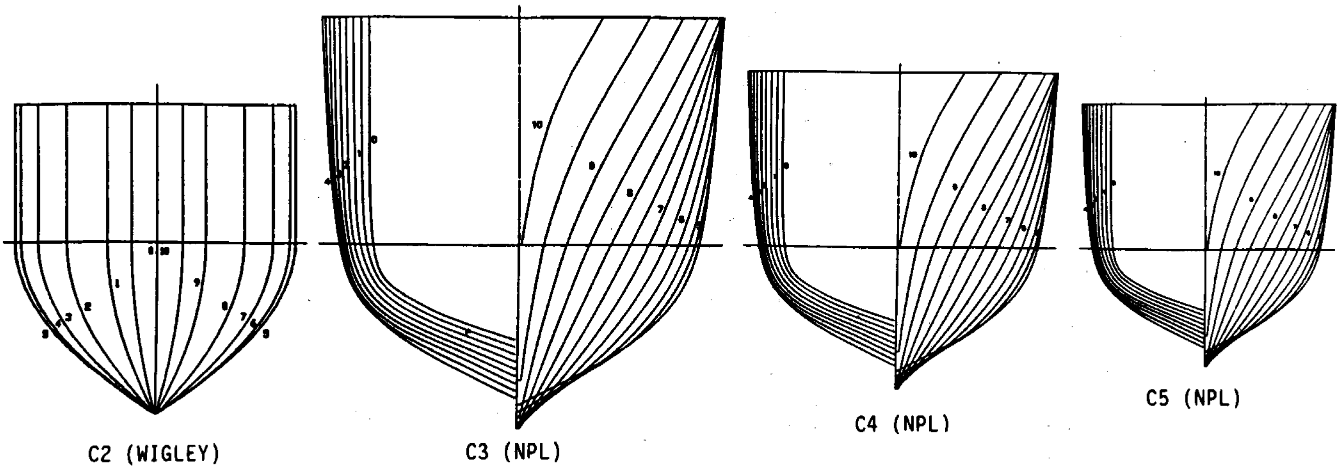
C2 (WIGLEY)
C3 (NPL)
C4 (NPL)
C5 (NPL)

Fig. 1a Body Plans of Models Tested (all drawn to same scale)

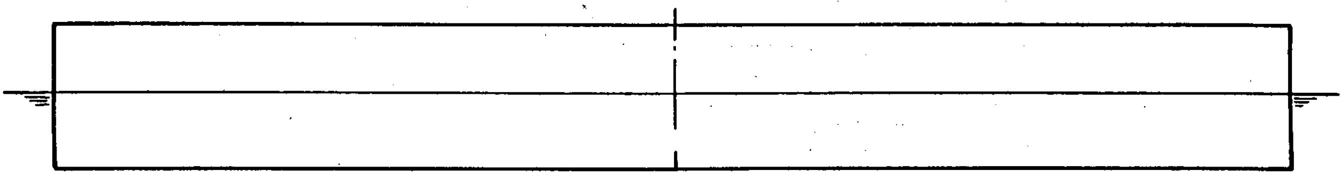

Fig. 1b Hull Profile of Wigley Form

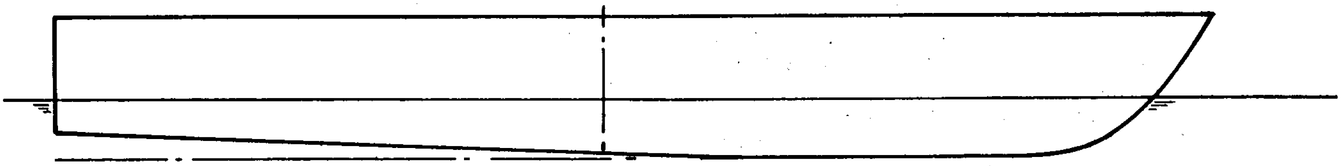

Fig. 1c Hull Profile of NPL Forms

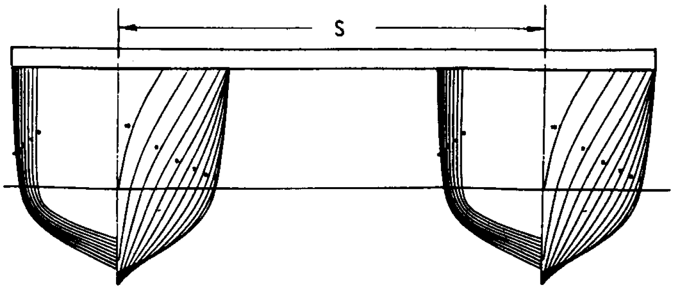

Fig. 2 Example of the Models (C5) in Catamaran Configuration (S/L = 0.2)

microcomputer based data acquisition system and data analysis software enabling the determination of the results during standard resistance tests.

All wave probes were located at an optimum longitudinal position for longest possible wave traces, whilst transverse positions of the probes were chosen to obtain a suitable cosine term in the wave series for every harmonic. This has an important effect on the stability of the analysis enabling the results to be effectively independent of the probe transverse positions. The analysis method is based on a combined matrix solution of four longitudinal wave traces. The method takes short wave traces into account without truncation corrections.

Successful validation of the method was conducted by comparing the results for the Wigley model, both as a monohull and a catamaran, with the results in Refs. 6 and 3 respectively. A full description of the apparatus and analysis method is given in Ref. 8.

3.3 Viscous Resistance

Viscous resistance was obtained by means of a wake traverse analysis. A wake traverse rig consisting of a rake with 24 pitot tubes, 12 2-way solenoid valves and 12 pressure transducers together with a microcomputer based data acquisition system was developed for use in the wake surveys. The rake was mounted on a two way movement table with facilities for 250mm lateral and 300mm vertical adjustment within an accuracy of 0.1mm, allowing a complete survey to be made through the wake of the models. The analysis for viscous resistance was carried out using the Melvill-Jones method. A full description of the background design of the rig and the analysis system is given in Ref. 8.

Due to the extensive time required for such tests, the wake investigation was limited to two models (C2, C3) and a limited number of speeds (Fn = 0.35, 0.50 and 0.75). Validation of the current setup was made by comparing the wake survey results with available published data for the Wigley hull, Ref. 5.

3.4 Trim and Sinkage Measurements

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

4. PRESENTATION OF DATA

The total resistance of a catamaran, in coefficient form, may be expressed as:

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

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
ϕ is introduced to take account of pressure field change around the demihull
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
τ is the wave resistance interference factor.

For practical purposes, ϕ and σ can be combined into a viscous resistance interference factor β,
where $(1+\phi k)\sigma = (1+\beta k)$

whence $$C_{Tcat} = (1 + \beta k)\, C_F + \tau\, C_W \qquad (2)$$

noting that for the demihull in isolation, $\beta = 1, \tau = 1$.

The measured experimental data are presented in Figs. 3 to 10. Figs. 3 to 6 give the total and wave pattern resistance data for the demihulls (or monohulls) in isolation whilst Figs. 7 to 10 give these data for the catamaran configurations. Results of the viscous traverse experiments are also included in Figs. 3, 4, 7, 8 and 11.

C_W, viscous interference factors β and wave interference factors τ are derived from the experimental data, as discussed next in Section 5, and are presented in Figs. 12 to 14. Figs. 15 to 18 present the results of the trim and sinkage measurements, whilst Figs. 19 and 20 present theoretical predictions.

5. DISCUSSION OF RESULTS

5.1 Total Resistance and Wave Pattern Resistance

Monohulls:

The results of the total and wave pattern resistance measurements for the monohulls are shown in Figs. 3 to 6. The total resistance measurements are of the general form to be expected and both the Wigley model (C2) and the round bilge transom forms (C3, C4, C5) showed satisfactory correspondence with published monohull data.

The results of the wave pattern measurements are included in Figs. 3 to 6 and are plotted downwards from the total resistance values. The results for the Wigley hull in Fig. 3 show some small undulations in wave pattern resistance at lower Froude numbers before settling down to an approximately constant level above the ITTC friction line at higher Froude numbers. The results for the round bilge transom stern models shown in Figs. 4, 5 and 6 display a hump (or decrease in measured wave pattern resistance) at a Froude number of about 0.42 before settling down at an approximately constant level above the ITTC friction line at higher Froude numbers. Observations during the tests and results of the viscous traverse experiments described in the next section, confirmed that the large hump is due primarily to transom stern and wave breaking effects and should therefore not be included in the viscous component.

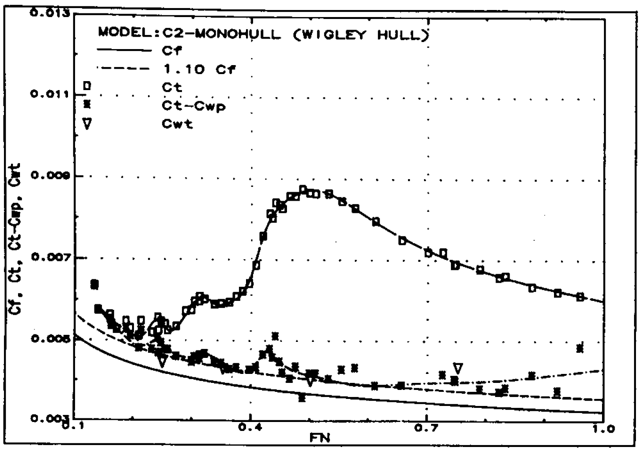

Fig. 3 Resistance Components (Model C2: Monohull)

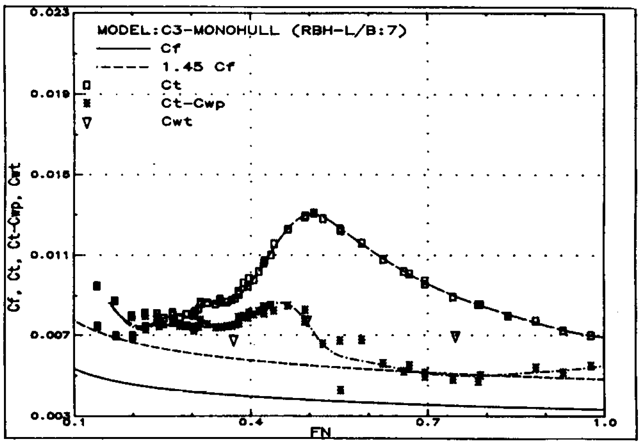

Fig. 4 Resistance Components (Model C3: Monohull)

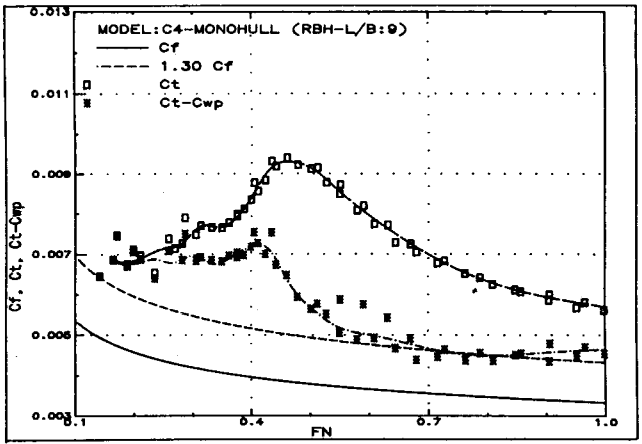

Fig. 5 Resistance Components (Model C4: Monohull)

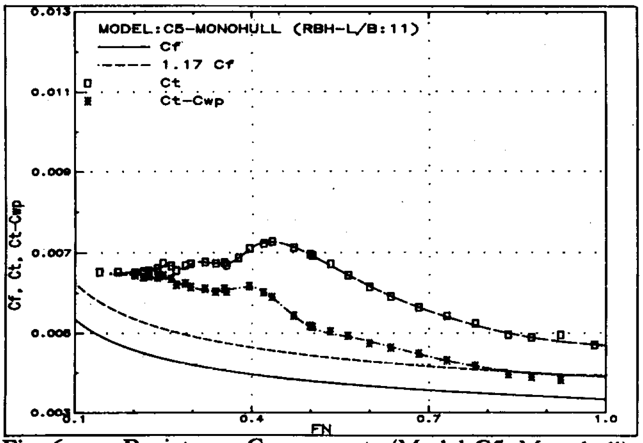

Fig. 6 Resistance Components (Model C5: Monohull)

Catamarans:

The total and wave pattern resistance measurements for the catamaran configurations, shown in Figs. 7 to 10, indicate broadly similar trends to those of the monohulls, except in these cases wave interference effects are present and viscous interference effects cause the wave pattern results to lie somewhat higher above the friction line.

It should be noted that some difficulty was encountered in acquiring satisfactory data at the lowest separation ratio, S/L = 0.2, for the Wigley form and the fullest round bilge form (C3). This was due to substantial wave breaking between the hulls which also curtailed testing at higher speeds due to possible swamping of the models.

5.2 Viscous Resistance

The results of the viscous traverse experiments carried out for the Wigley model, C2, are included in Figs. 3 and 7a, 7b , 7c.

In the case of the Wigley monohull, Fig. 3, the viscous resistance values are close to the (C_T - C_{WP}) results. The results suggest that a form factor (1+k) of 1.10 would be appropriate for this model, and this is in broad agreement with published results where (1+k) has been obtained with larger models from low speed tests. The results also indicate that, for practical purposes, the form factor should be kept constant across the speed range.

The viscous resistance results for the Wigley hull in catamaran configurations, Figs. 7a, 7b and 7c also show reasonable agreement between (C_T - C_{WP}) and C_{WT}. In these catamaran cases the total viscous resistance is seen to be higher than the demihull in isolation, indicating the presence of viscous interference. Some examples of wake contours for one of the Wigley hull catamarans are shown in Figs. 11a, 11b and 11c. These illustrate the effect of asymmetric flow on the shape of the viscous wake behind the stern at different speeds.

The results of the viscous traverse experiments carried out for the round bilge model, C3, are included in Figs 4 and 8a, 8b, 8c. Like the results for the Wigley model, there is generally reasonable agreement between (C_T - C_{WP}) and C_{WT}.

The viscous wake analysis is very time consuming and would not be recommended for routine commercial testing unless the system is automated, for example as described in Ref. 9. Also, the achievement of a satisfactory standard of accuracy can often be difficult. The viscous measurements do however broadly confirm that, for higher speed displacement monohulls, where transom sterns and wave breaking effects for such craft normally preclude the satisfactory derivation of form factors at low speeds, the derivation of form factors from total minus wave pattern resistance over a higher speed range offers a plausible approach. It follows that a similar approach for catamarans will yield viscous interference factors as defined in Equation 2. The routine use of the method is further simplified when a fully automated wave acquisition/analysis system is available, such as that developed for the current work.

It is noted from Figs. 3 to 10 that the siting of (1+k) C_F (or (1+βk) C_F for catamarans) has to be made with care and will normally be no higher than a lower envelope around the wave pattern data. The weight of experimental evidence offered in Figs. 3 to 10 does however indicate that this approach can be implemented satisfactorily.

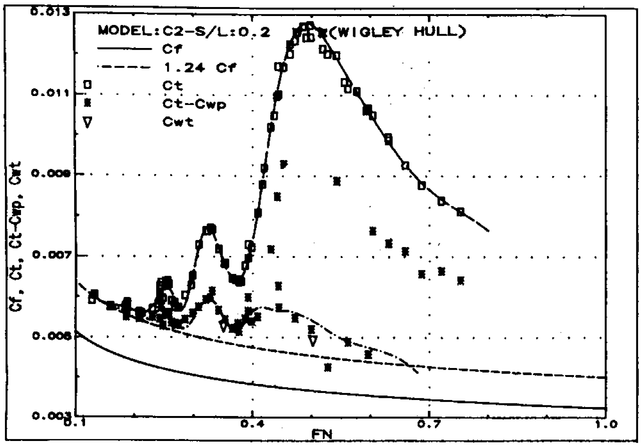

Fig. 7a Resistance Components (Models C2: S/L=0.2)

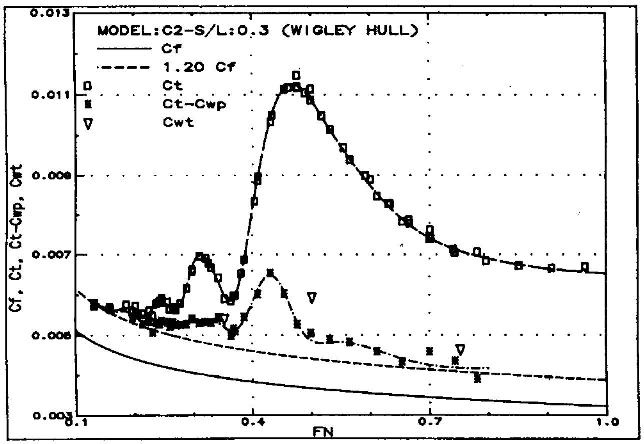

Fig. 7b Resistance Components (Models C2: S/L=0.3)

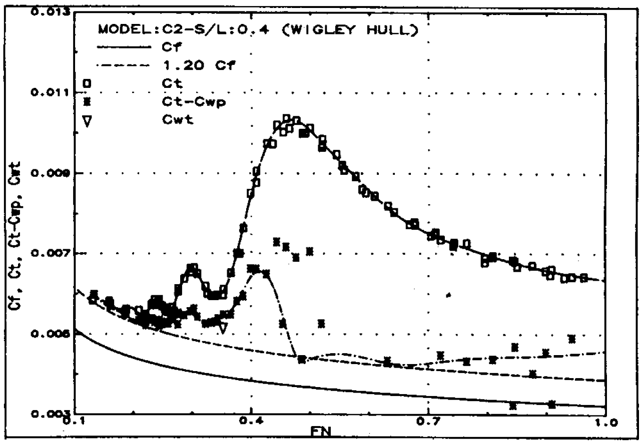

Fig. 7c Resistance Components (Models C2: S/L=0.4)

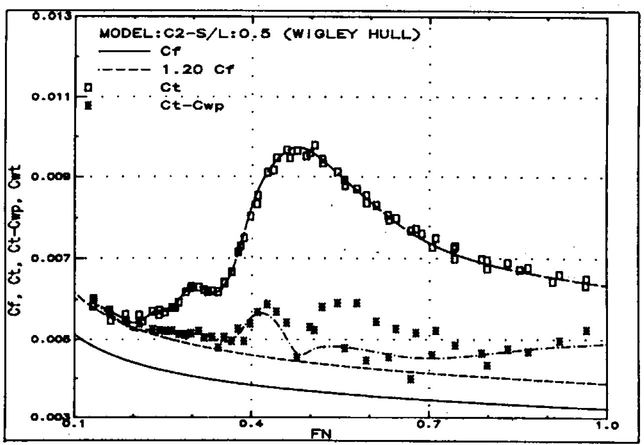

Fig. 7d Resistance Components (Models C2: S/L=0.5)

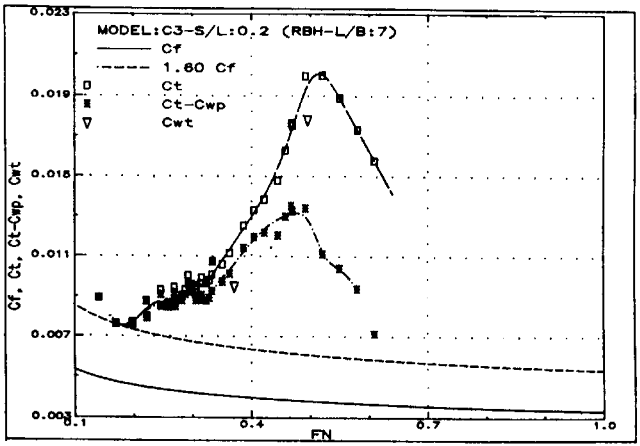

Fig. 8a Resistance Components (Models C3: S/L=0.2)

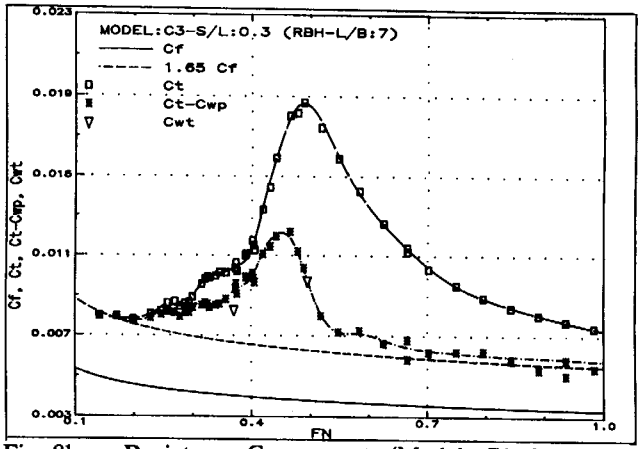

Fig. 8b Resistance Components (Models C3: S/L=0.3)

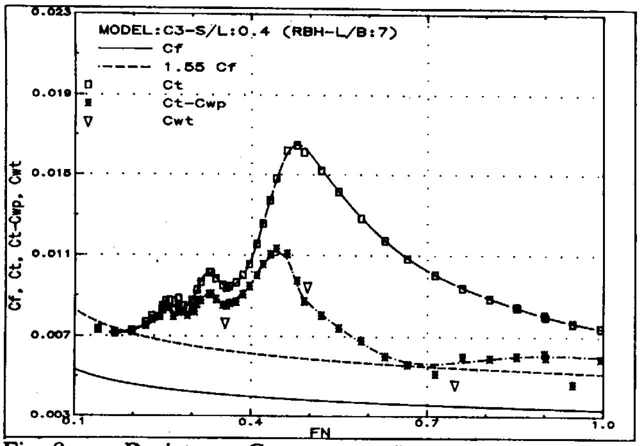

Fig. 8c Resistance Components (Models C3: S/L=0.4)

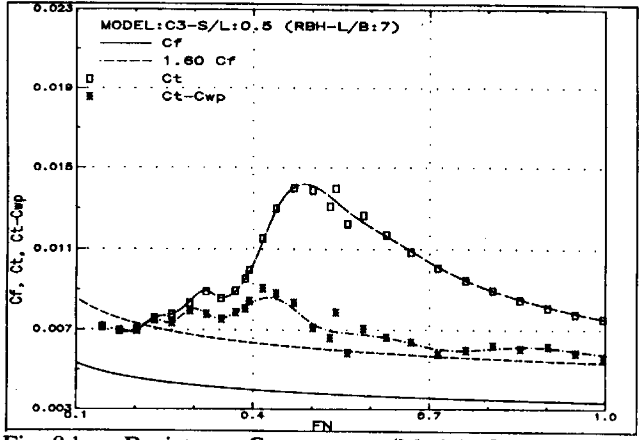

Fig. 8d Resistance Components (Models C3: S/L=0.5)

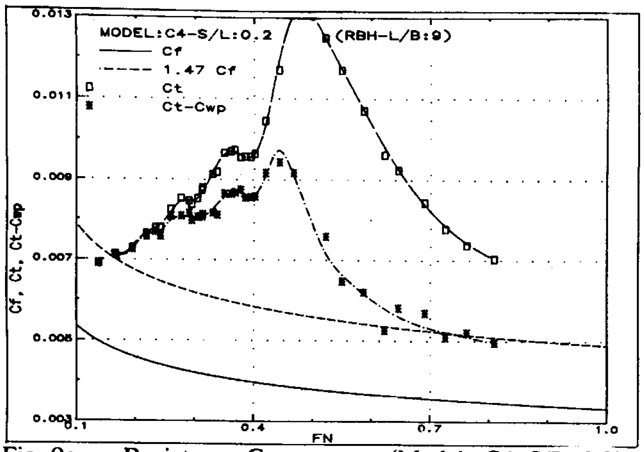

Fig. 9a Resistance Components (Models C4: S/L=0.2)

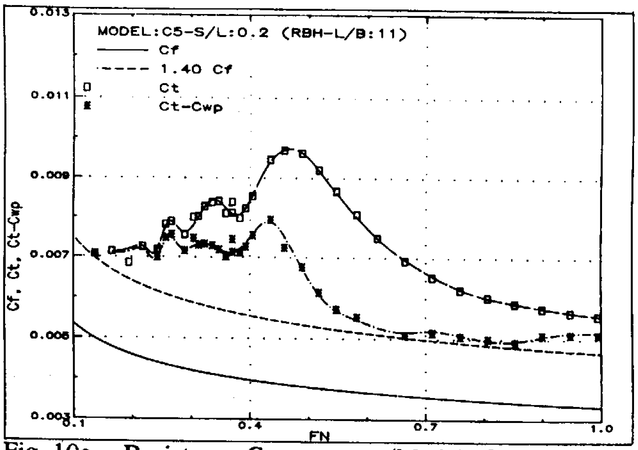

Fig. 10a Resistance Components (Models C5: S/L=0.2)

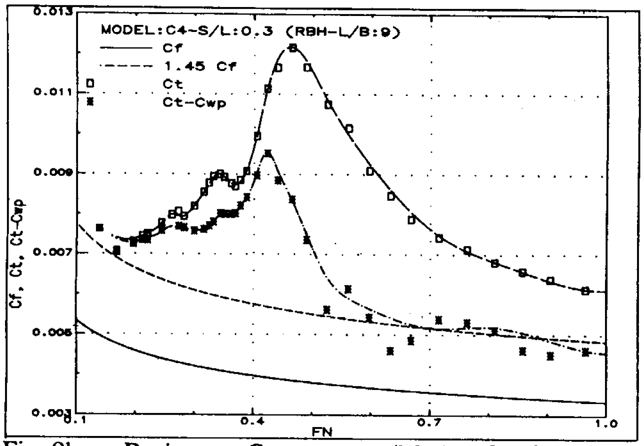

Fig. 9b Resistance Components (Models C4: S/L=0.3)

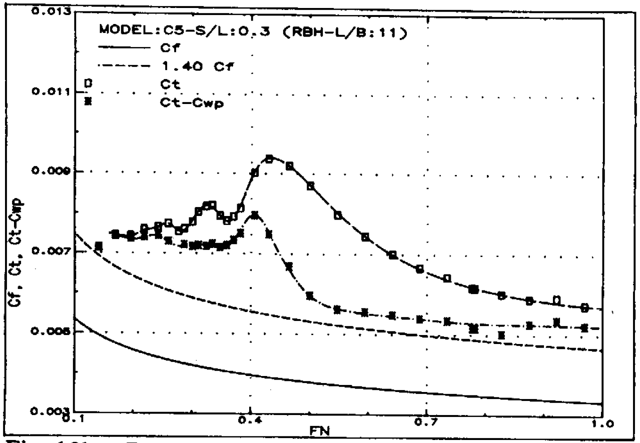

Fig. 10b Resistance Components (Models C5: S/L=0.3)

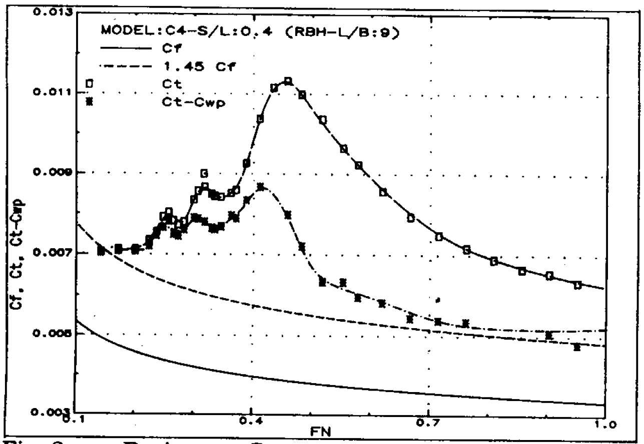

Fig. 9c Resistance Components (Models C4: S/L=0.4)

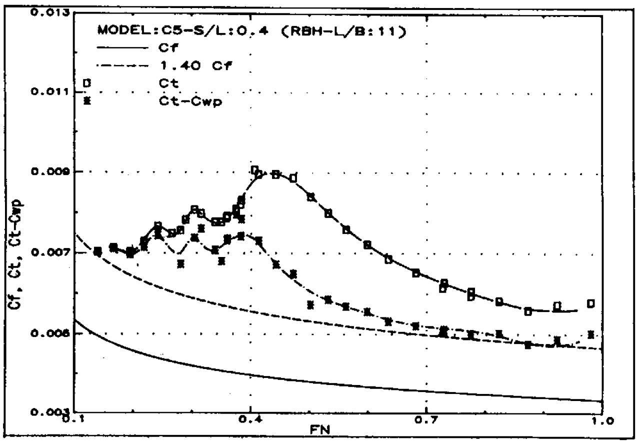

Fig.10c Resistance Components (Models C5: S/L=0.4)

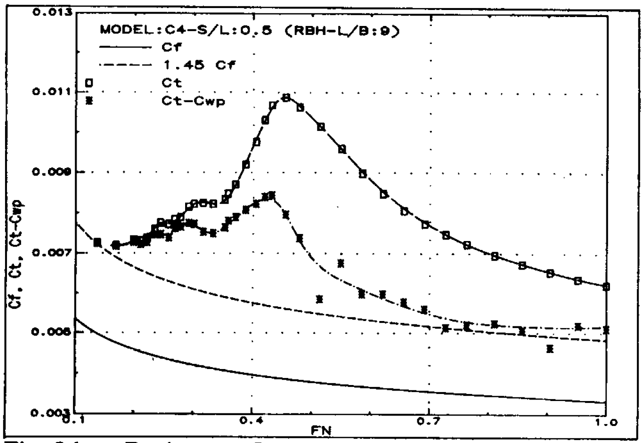

Fig. 9d Resistance Components (Models C4: S/L=0.5)

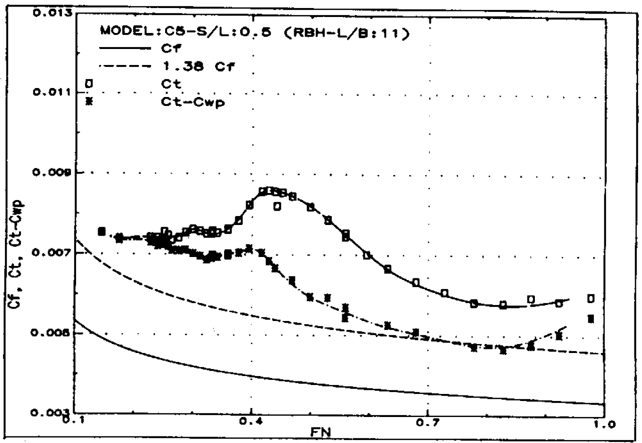

Fig. 10d Resistance Components (Models C5: S/L=0.5)

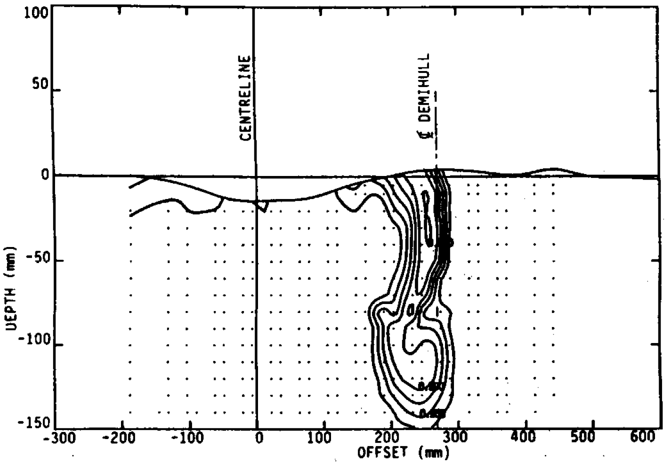

Fig. 11a Wake Contours (Models C2: S/L=0.3) Fn=0.35

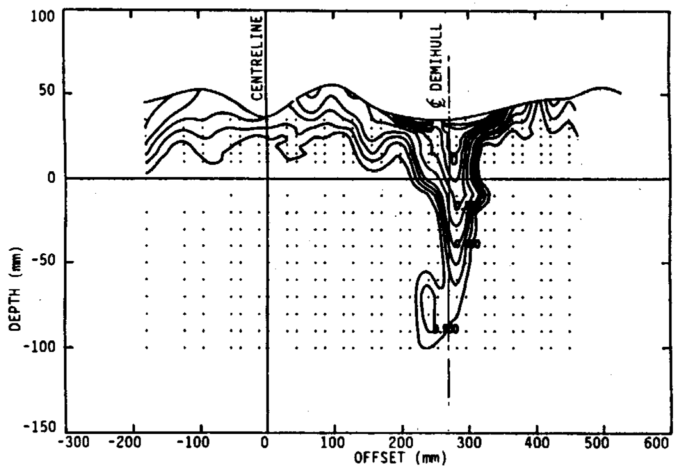

Fig. 11b Wake Contours (Models C2: S/L=0.3) Fn=0.50

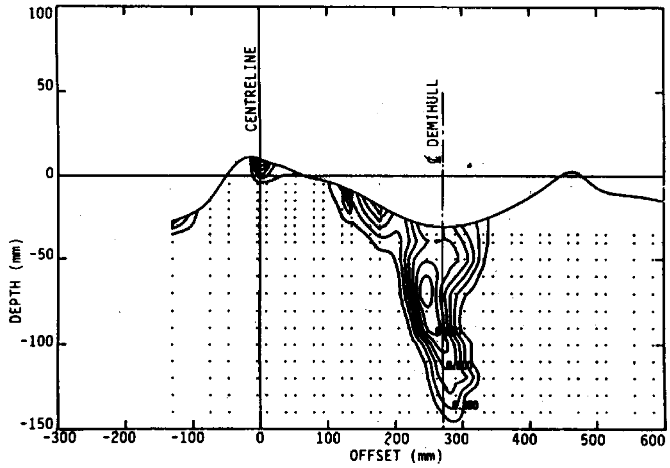

Fig. 11c Wake Contours (Models C2: S/L=0.3) Fn=0.75

TABLE II Derived Form Factors for the Models in Monohull Configuration

MODEL	C2	C3	C4	C5
(1+k)	1.10	1.45	1.30	1.17

5.3 Wave Resistance, C_W

The derived wave resistance coefficient, C_W, for the monohulls is shown in Fig. 12. C_W is defined as $(C_T-(1+k)C_F)$, using the derived monohull form factors discussed in the previous section and given in Table II.

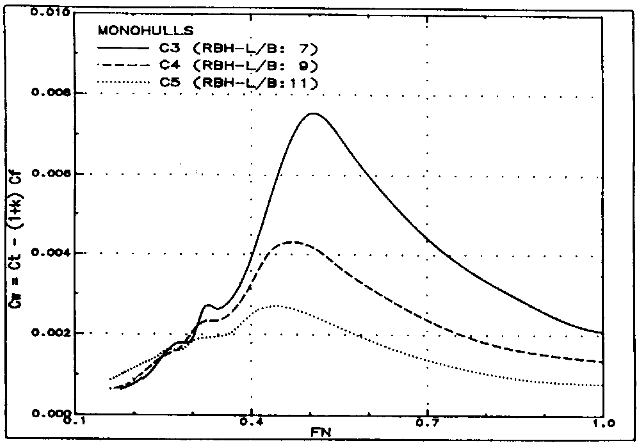

Fig. 12 Wave Resistance C_W for Models C3, C4, C5

5.4 Catamaran Viscous Resistance Interference

The viscous resistance interference factors β derived from the work are shown in Fig. 13. β is defined in Equation 2 and has been derived using the monohull form factors given in Table II. The wave pattern and viscous results for the catamarans indicate that β is effectively independent of speed and, for practical purposes, should be kept constant across the speed range. Fig. 13 indicates that β varies from about 1.3 to 2.3 depending primarily on L/B ratio. It is interesting to note that S/B (hence S/L in this case) would appear to have little influence on β except for the Wigley hull which does, as might have been expected for all the models, show some increase in β with decrease in S/B.

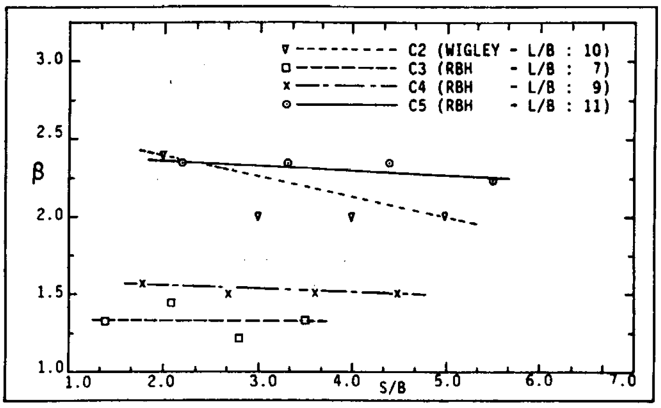

Fig. 13 Variation of Viscous Interference Factor β with S/B

5.5 Catamaran Wave Resistance Interference

The wave resistance interference factors τ, for different S/L ratios, are given in Figs. 14a to 14d. From Equation 2, τ is defined as:

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

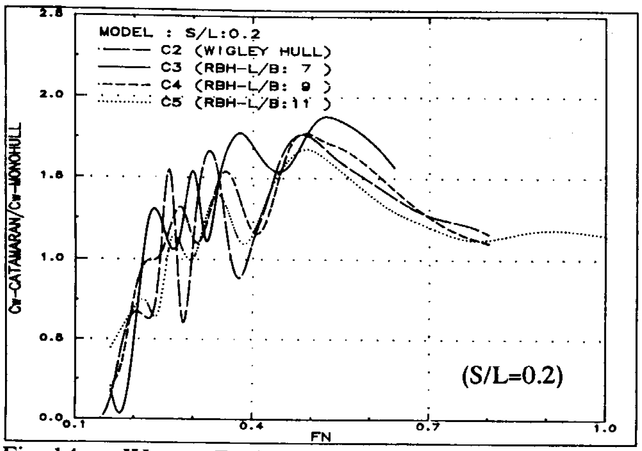

Fig. 14a Wave Resistance Interference Factor τ

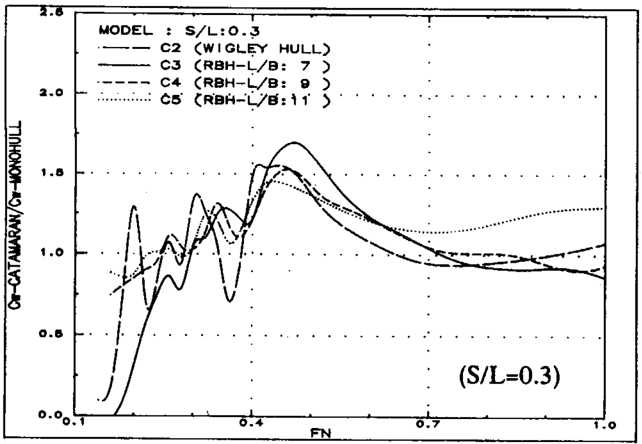

Fig. 14b Wave Resistance Interference Factor τ

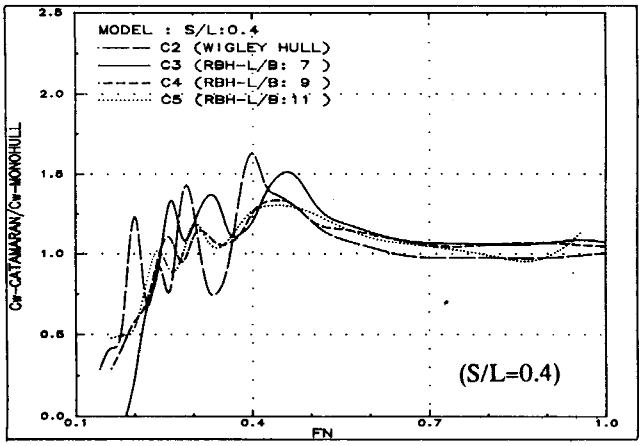

Fig. 14c Wave Resistance Interference Factor τ

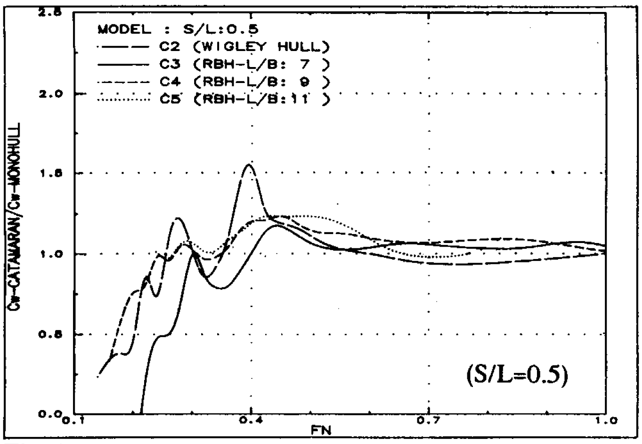

Fig. 14d Wave Resistance Interference Factor τ

where for practical purposes (1+k) and β have been assumed constant across the speed range, as discussed earlier.

The results indicate that higher separations result in smaller wave interference with humps and hollows located at lower Froude numbers. It is also noted that there is a change in the interference phasing and amplitude with change in L/B ratio. With smaller L/B ratios larger interference effects are obtained and the humps and hollows are positioned at higher Froude numbers.

Beneficial wave interference is found at about Fn = 0.35 to 0.42 whilst adverse effects are found both sides of this speed range. The wave interference can effectively be neglected above a particular speed which is both separation and L/B ratio dependent. This is an interesting and important result since it suggests that, for higher speed designs, the choice of hull spacing may be based on other requirements such as seakeeping performance without incurring significant penalties in calm water resistance.

5.6 Sinkage and Trim

The interference effects on running trim and sinkage of the hulls are given in Figs. 15 to 18. Trim angle interference is important between Fn = 0.3 and 0.7 where the catamaran displays higher trim angles than the monohull but approximates to the monohull trim angle as separation distance is increased. Outside this region there are no significant trim interactions. It can also be noted that the significant trim interference occurs where the catamaran wave resistance shows severe adverse interference.

Sinkage of the catamarans is significantly higher than the monohulls up to about Fn = 0.5 and less above this speed. The increased sinkage at the lower and intermediate speeds may be of importance when considering catamaran freeboard and cross structure clearances.

6. THEORETICAL WAVE RESISTANCE

Linearised wave resistance theory was applied to obtain theoretical predictions. The far field wave system for a Kelvin source in a shallow water canal was developed. In order to establish an analytical approach to the wave resistance, wave coefficients for a ship model were obtained using this method and the assumption of thin ship theory; the wave resistance is then obtained from these coefficients. The method can be applied to any slender hull shape and any number of hulls in the tank. Modifications to the basic theory are included to take account of transom sterns, sinkage and trim. A full description of the development of the theory is given in Ref. 8. The method was applied to catamaran configurations to obtain the wave interference resistance.

Examples of applications of the theory, and comparisons with experimental results, are given in Figs. 19 and 20. It is seen that, whilst the theory overestimates the wave resistance, the trends due to changes in parameters are in broad agreement particularly when viewed on a comparative basis. The theory thus provides a useful design tool at the preliminary design stage for screening suitable combinations of hull parameters and hull spacing.

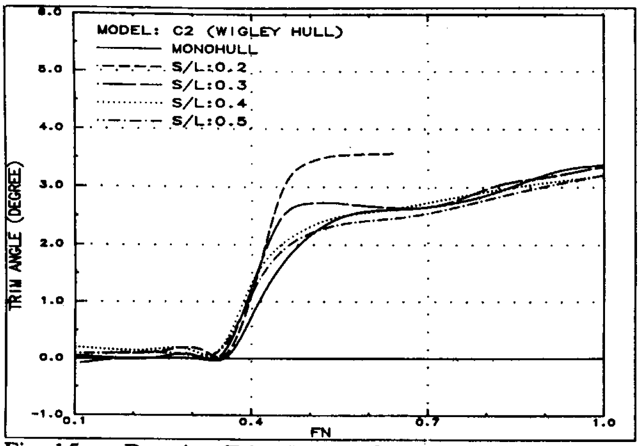

Fig. 15a Running Trim (Model C2)

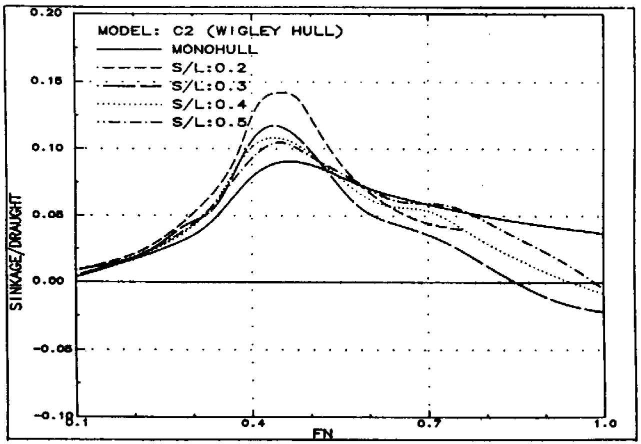

Fig. 15b Sinkage (Model C2)

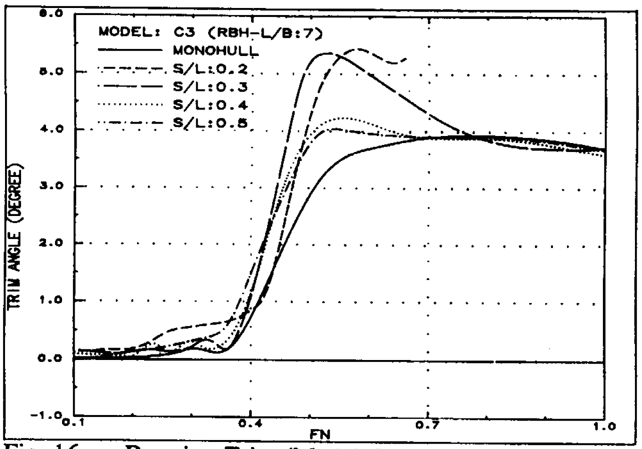

Fig. 16a Running Trim (Model C3)

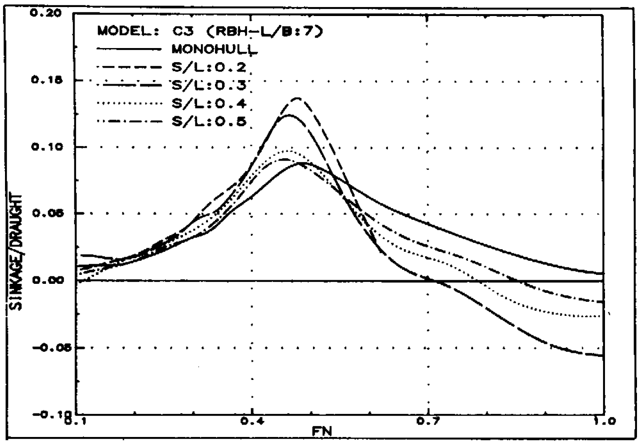

Fig. 16b Sinkage (Model C3)

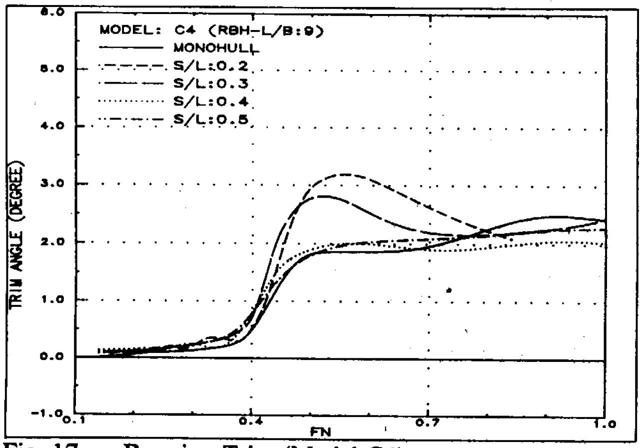

Fig. 17a Running Trim (Model C4)

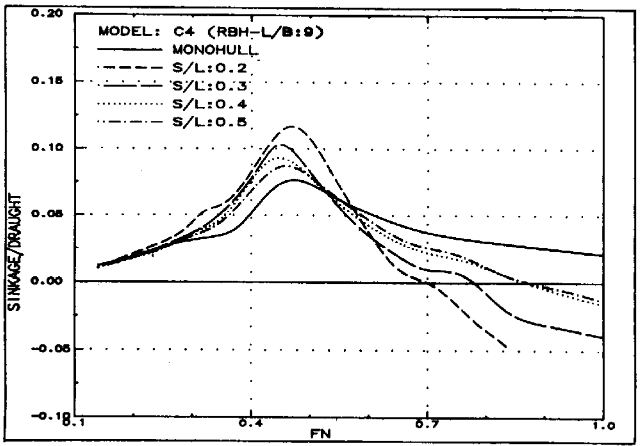

Fig. 17b Sinkage (Model C4)

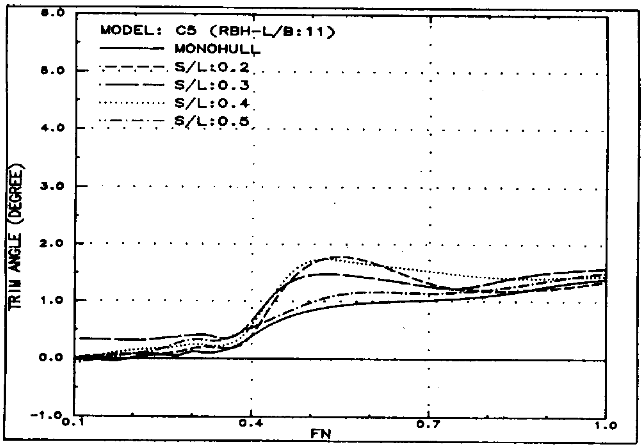

Fig. 18a Running Trim (Model C5)

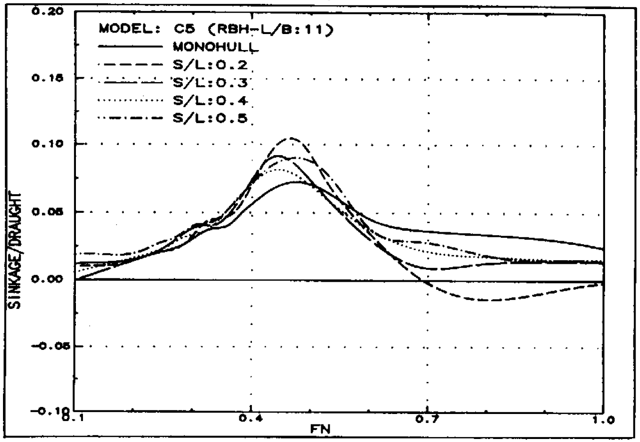

Fig. 18b Sinkage (Model C5)

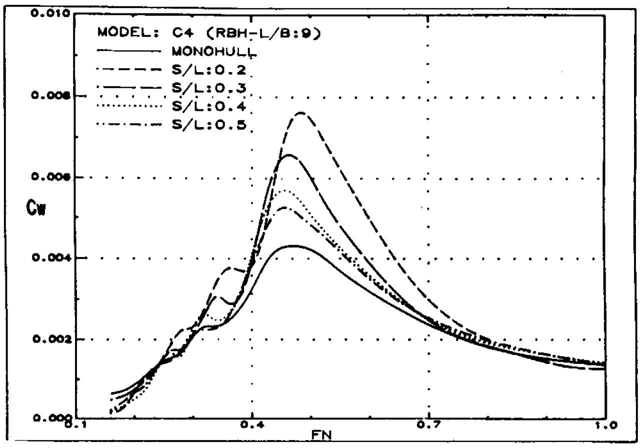

Fig. 19a Wave Resistance (Model C4)

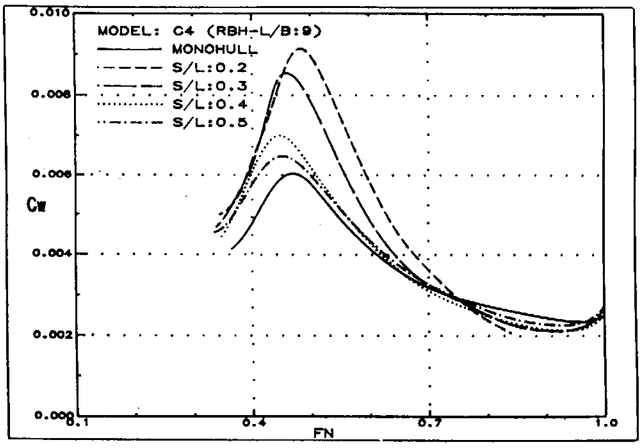

Fig. 19b Theoretical Wave Resistance (Model C4)

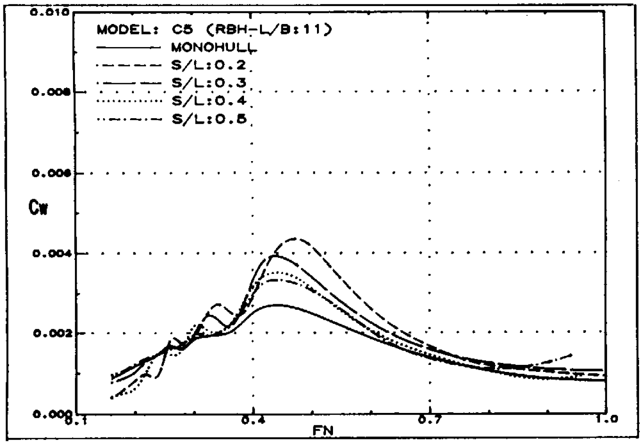

Fig. 20a Wave Resistance (Model C5)

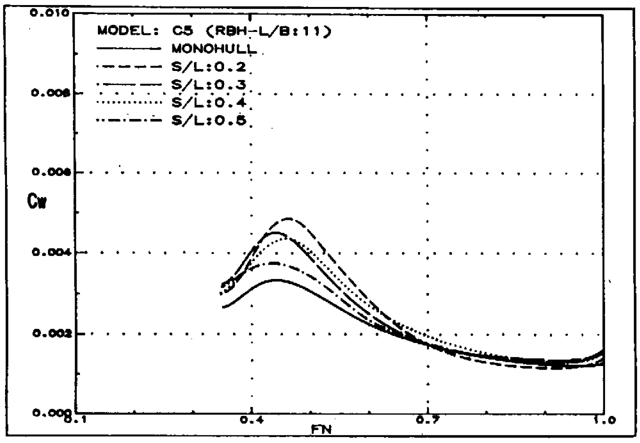

Fig. 20b Theoretical Wave Resistance (Model C5)

7. PRACTICAL RESISTANCE ESTIMATION

Using the results of the current work a practical preliminary resistance estimate is available for catamarans with forms broadly similar to those tested.

The method can employ the monohull form factors given in Table II, the viscous interference factors given in Fig. 13, the monohull wave resistance coefficients given in Fig. 12 and the wave interference factors given in Fig. 14 all of which can be assembled in Equation 2 to give C_T.

The results of a theoretical investigation reported in Ref. 8 indicated that the wave interference factor was relatively insensitive to changes in some hull form parameters such as B/T. Thus whilst the experimentally derived interference factors should strictly be applied to the hull forms of the current work, it is considered that, providing the forms are broadly similar to those tested, the factors could also be applied to values of (1+k) and C_W derived from independent sources such as standard series data.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 The investigation provides a better understanding of the resistance components in calm water of high speed displacement catamarans. The results for the monohulls tested as part of the investigation indicated that such vessels can have an appreciable viscous form effect. This effect is higher in the case of the catamaran where viscous interference takes place between the hulls. It is thus believed that form effect should be included in the extrapolation procedure for these vessel types if realistic resistance predictions are to be made.

8.2 The viscous wake traverse system provided a satisfactory method of obtaining the viscous drag of catamarans, and the sum of the viscous and wave pattern resistance achieved a budget reasonably close to total resistance. It thus confirmed the alternative method for the derivation of total viscous resistance, that is from the difference between total and wave pattern resistance.

8.3 The automated wave pattern analysis system, developed for the investigation, proved to be successful over a wide range of speeds, providing very valuable information on the wave interference of catamarans as well as achieving a direct method for the determination of form factor. Additionally, the data improve the knowledge of wave pattern resistance for monohulls at high speeds.

8.4 Viscous resistance interference was found to be dependent primarily on demihull length to beam ratio but to be effectively independent of speed and hull separation.

8.5 At lower speeds there is a change in the wave resistance interference phasing and amplitude with change in L/B ratio. Above a critical speed, which is separation dependent, the wave interference can be neglected. This is an important feature for higher speed vessels since it allows hull spacing to be optimised for other design considerations, such as ship motions.

8.6 It was found that the values of trim and sinkage for the catamaran can be substantially different from the monohull and need to be borne in mind when freeboard and clearance of cross structure are being considered.

8.7 The theoretical investigation indicated that modified thin ship theory can provide a useful preliminary design tool for investigating comparative changes in wave resistance due to changes in hull form parameters and hull spacing.

8.8 The current investigation has identified the effects of separation and L/B ratio on the resistance interference factors. Similar experimental investigations for the effect of C_p and B/T (which is not stability limited as in the case of the monohull) are recommended in order to completely understand hull form effects.

8.9 The investigation of resistance components has indicated the likely suitable breakdown of the components for extrapolation to full scale. Confirmation of this aspect would depend on full scale trial results which are currently not available. Such a model-ship correlation exercise is necessary if the extrapolation methods for this particular ship type are to be validated.

NOMENCLATURE

DEMIHULL	-	One of the hulls which make up the catamaran (in the current investigation all demihulls are symmetrical)
A	-	Wetted surface area (static condition)
B	-	Breadth of demihull
L	-	Length on still waterline
S	-	Separation distance between centrelines of catamaran hulls
T	-	Draught
∇	-	Displacement volume
V	-	Speed
Fn	-	Froude Number ($V/\sqrt{gL}$)
Rn	-	Reynold's Number (VL/ν)
C_B	-	Block Coefficient
C_p	-	Prismatic Coefficient
C_T	-	Total Resistance Coefficient (Resist/$1/2\rho AV^2$)
C_F	-	Frictional Resistance Coefficient (ITTC 1957 line)
C_W	-	Wave Resistance Coefficient
C_{WP}	-	Wave Pattern Resistance Coefficient
C_{WT}	-	Viscous Wake Traverse Resistance Coefficient
(1+k)	-	Form Factor
β	-	Viscous Resistance Interference Factor
τ	-	Wave Resistance Interference Factor
ρ	-	Water Density
ν	-	Water Kinematic Viscosity

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DISCUSSION

Professor R.K. Burcher Ph.D., R.C.N.C., F.Eng. (Fellow): As I am first to speak I would like to congratulate the authors on presenting the paper, and also to thank them very much because, as I see it, this is a considerable increase in the amount of information available on the resistance of high speed catamarans. Some of our students, attempting to carry out multi-hull ship designs have encountered an almost total lack of information, particularly in this higher speed range.

This led us to building a model of one of our student's designs, and to conducting some resistance tests and I would like to raise a few points arising from our results.

We found that in the range of 0.4 to 0.7 Froude number, there still seem to be some oscillatory components which do not appear to be in Figs. 14(a)-(d) in your paper. This varies with hull spacing and there appeared to be an optimum of about 0.4 spacing-to-length ratio that was of lower resistance than the others. There are some doubts about the measurements we have taken so far, but there was also some confirmation. We observed quite a considerable upwelling between the hulls at the points where we were measuring higher resistance.

I would like to ask the authors: when you did wave pattern measurements, presumably astern of the vessel, did you record or observe any wave or surface distortion between the hulls? A possible cause of the difference is that our model had asymmetric hulls, they were almost straight inside with a slight bow shaping rather than your symmetric hulls. This does raise another question, we cannot adopt the process used in your paper of comparing the difference between the monohull and the two hulls together. I have some doubts about the validity of carrying out a monohull test on an asymmetric hull to get the frictional resistance. As an alternative, we measured the resistance with the hulls very widely spaced, but unfortunately, looking at the results, I suspect we encountered tank wall interference in this condition. Perhaps you would like to comment on how one would deal with asymmetric hull forms.

Mr D. Bailey (Fellow): This is a very timely paper and I would like to congratulate the authors for putting it before the Institution today.

It is increasingly obvious that catamarans are becoming more popular in the high speed passenger ferry field. Apart from Everest's work for low speed catamarans, there is little the designer can turn to for wider information on the resistance or interference factors of twin hulls so now that the authors' paper takes us up to unity Froude number it is very welcome indeed.

It is of interest to see that at higher speeds the interference between two similar monohulls when brought together in a catamaran configuration is so small that for S/L=0.4 and above it can be ignored. S/L=0.4 appears to be a separation ratio that can be realistically adopted in practice and designers will be encouraged by such a minimal effect.

Quite rightly, the paper concerns itself with the estimation of full scale power from a model test result and in this respect conclusion 8.9 is relevant today because for displacement ships the correction factors applied to model test results to give estimates of full scale speed and power are of course the all important correlation factors which have been derived and refined over the years from the huge and successful programme of ship-model comparison studies conducted by BSRA, NPL and others. This correlation factor is really a blanket correction in which various unexplained differences such as the effect of form on the two-dimensional friction extrapolator, propulsion scale effects, etc. are lumped together. Such correlation factors are more accurate if they relate to specific ship types and ideally they will need to be derived for catamarans. It is worrying that ship-model comparison studies are no longer in progress. As modern ship shapes evolve, today's correlation factors may well become unsuitable, thereby reducing the accuracy of prediction. If we are unable to keep our correlation factors up to date then I believe at least one of the uncertainties in scaling model results can be removed by including in the analysis a form factor for the hull considered and so I agree with the approach in this paper where a form factor, k, is included in equation (1). However, it is important that this factor is determined with accuracy.

Our understanding of form factor is seen by the increase in viscous resistance due to a three-dimensional body over that calculated from a two-dimensional viscous formulation. It is a value which is entirely independent of wavemaking effects and I would prefer to derive it from the model test using the system as developed by Hughes or Prohaska. These use low speed model measurements where wavemaking is so small as to be negligible. The authors' approach of measuring wave pattern disturbance and then deducting derived wave resistance from total resistance does perhaps imply some uncertainty over achieved accuracy. Prohaska's method described in the Proceedings of the 11th ITTC has the added virtue of allowing a check on the possibility of laminar flow, should it exist, over the model surface. In this context, I wonder whether results at 0.5 million Reynolds number are truly reliable. Also I am surprised at the value of the form factor for the C3 monohull. This is surely too high at 1.45. C3 is not greatly different to the parent form of Ref. 7; the form factor for that form came out at 1.126, slightly higher than Wigley's mathematical hull which as the authors say has been confirmed elsewhere as 1.10. The Wigley form is very fine, as is the parent of Ref. 7, and I find it difficult to believe that the form factor for C3 (whose fineness lies somewhere between Wigley and the parent) should be as high as the authors suggest. Running trim for the C3 monohull (Fig. 16a) is also unexpectedly high at $L/\nabla^{1/3}$=6.27, 2½ degrees at F_n=0.7 being more likely. I wonder if this may indicate that the resistance of the C3 monohull may be in doubt.

Mr G.E. Gadd, M.A., Ph.D. (Member): I share the enthusiasm of the previous two speakers for the paper but I am not sure that I fully accept the conclusions of the authors regarding the form factors, and particularly concerning the variation of viscous form factor between catamarans and monohulls.

The implication of an equation such as No. (2) of the paper is that the resistance can be divided into a component that is primarily Froude number dependent, but independent of Reynolds number, and another that is primarily Reynolds number dependent but independent of Froude number.

The authors propose to estimate an effective viscous form factor to be applied over the whole speed range, from the ratio of (total resistance minus wave pattern resistance) to flat plate friction resistance at high speeds. This they claim will obviate anomalies due to transom sterns and wave breaking effects. (One may interpolate here that the presence of a transom stern of course may make it difficult to adopt the Prohaska approach just advocated by the previous speaker).

However, although at high speeds the flow will separate more cleanly from a transom stern, this is not to say that there will be no wave breaking effects present. Moreover, such wave breaking will probably be more important in a catamaran configuration, due to the doubling effect of wave height on the catamaran centre line. Thus Fig. 11(c) shows that even at Froude number 0.75 for a form without a transom stern, there are significant wave breaking losses on the centre line. Accordingly, the wave pattern resistance at high speeds will not include all of the Froude number dependent part of resistance and this shortfall can be expected to be greater in catamaran configurations. This perhaps throws some doubt on the propriety of using the factor β in equation (2).

On another point, did the authors observe the point at which the flow first separated cleanly from the rather deep transom sterns of the round bilge forms? And if so, do these Froude numbers correlate with the speeds at which the C_T -C_{WP} curves diverge markedly from the C_T curves?

Mr D. Stinton, M.B.E., C.Eng., F.R.Ae.S. (Member): I seek education on what is probably a very basic question: when you have two hulls you show that your demi-hulls are quite symmetric in plan form; are there any great disadvantages in splitting a demi-hull down the centre line, treating it as a whole hull and simply moving it apart so that you have two flat walls in between?

It would seem to me, in this basic way, that maybe viscous interference and the trim and sinkage effects, come partly from the convergent, divergent, or venturi nozzle effect that you are getting between the hulls, and if you therefore put flat walls, would this have some beneficial effect?

Mr J.F. Wellicome, B.Sc., Ph.D. (Fellow): I have had the privilege over the last four or five years of watching this investigation grow and have had quite a number of conversations with both the authors over the period of time concerned. I would say all power to their elbow for having done it. I think it was a very worthwhile thing to do.

Clearly, Dr Gadd and, I suspect, Mr Bailey, have in mind the difficulty of deciding what is Reynolds number dependent and what is Froude number dependent. I would endorse that. Really, a lot of the additional discrepancy between total minus wave pattern and the flat plate line is in fact wave breaking. I do not think anybody knows at all how that varies with scale and it would be interesting to try and find out. One of the things I would like to do with one of these fast ferry catamarans would be to see whether we could actually do wave pattern analyses while the vessel travels up and down the Solent for instance, to try to get some larger scale information on this very particular point. I think it is crucial to the scaling exercise to know.

I want to mention something which is not said either in the paper or elsewhere. The diagram from the paper quotes Froude number in the usual sense of Froude number based on model length; what is not said is that with the particular tank and model length the Froude number based on water depth is about the same as the length Froude number. In fact, you are approaching a super critical condition at the top end of the speed range. I do know in commercial test work a number of occasions where the model test has gone super critical, and is subject to the effects of shallow water and finite channel dimensions generally on drag. I do not think we have any option but to do the test under these conditions, but we want to know what effect those things have in the scaling process of going from model to full size.

To some extent that is built in with the thin ship wave drag calculations. If you could show that you can calculate ratios of wave pattern drag between demi-hulls and a monohull using thin ship theory, then maybe you can devise some sort of shallow water and blockage correction factor at high speeds on that basis. It is something which I think does need a lot of attention because, when you are going this fast with any sensible sized model in any tank that I know of, shallow water is going to be a problem. I would like the authors' views on that.

Mr T.A. Dinham-Peren, B.Sc. (Graduate): In this paper it is claimed that viscous drag interference for catamarans has been demonstrated - I am not sure that this is the case.

It is worth pointing out that the model results are likely to be affected by blockage. The models are close to recognised limits for blockage for speed/depth ratio, hull cross section area to tank cross section area ratio, and model to tank side distance compared with model length.

It would be expected that as the spacing between the hulls increased to infinity, β would tend to a value of 1. In Fig. 21 the authors' β factors have been plotted against L/S and a best fit straight line put through the data. It is seen that as L/S → 0 (i.e. infinite hull spacing) β does not tend to 1. Of course the variation of β with L/S may well not be a straight line; all the same it seems odd that the greatest change in β should occur when L/S is less than 2 (and therefore S/L is greater than 0.5).

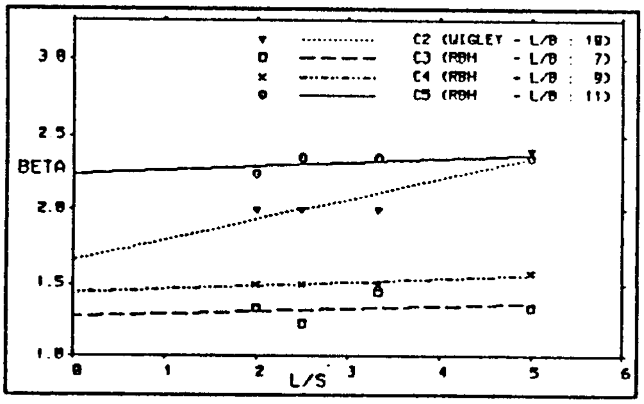

Fig. 21 Variation of Viscous Interference Factor β with L/S

In Fig. 22 the results for the C3 monohull and catamarans are plotted on the same figure. It will be seen that at low speeds the total resistance coefficient for the catamarans is less than for the monohull. It would seem that this figure does not support the idea that the catamarans' form factor is higher than that of the monohull.

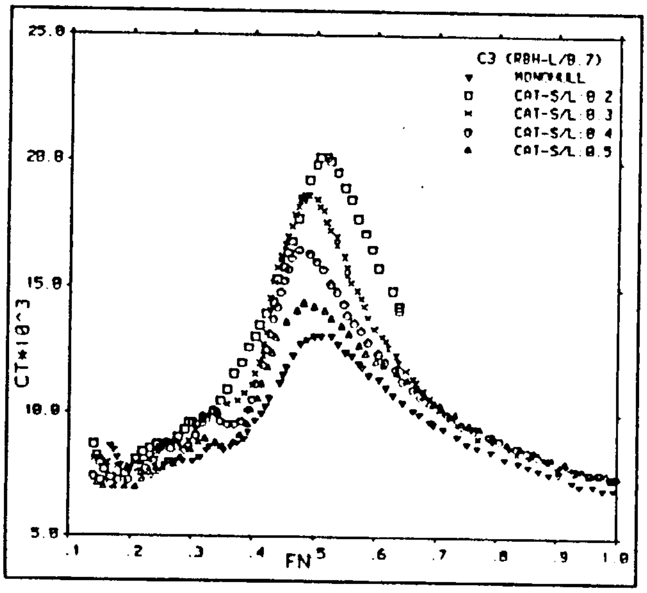

Fig. 22 C_T for C3 monohull and catamarans

For the Wigley hull form, which may be expected to have no residuary resistance at low speeds, Fig. 3 shows the (1+k).C_F curve lying below the C_T curve at low F_n, implying a non zero value for the residuary resistance coefficient, whereas in Figs. 7a,b,c and d the (1+k).C_F curve merges with the C_T curve.

For the round bilge forms, which would be expected to have some residuary resistance at low speeds due to their immersed transoms, Figs. 8,9 and 10 show no such resistance for the catamarans. But in contradiction to this, residuary resistance is shown at low speeds in Figs. 4,5 and 6 for the monohulls.

If it is assumed that the difference between the C_T and (1+k).C_F curves at slow speeds is similar for both monohulls and catamarans of the same hull design, and that the authors' figure of (1+k)=1.45 is taken to be correct for the C3 monohull, then values (1+k)=1.35, 1.44, 1.29 and 1.24 are calculated for the C3 S/L=0.2, 0.3, 0.4 and 0.5 catamarans respectively. This would tend to indicate that there is no viscous drag interference in this case.

Taking the above points into account, it would appear reasonable to assume that for all but the closest S/L spacings the form factor derived from the monohull can be applied directly to the catamaran. This assumption is useful in the preparation of resistance estimates.

If the wave interference factors were recalculated using this assumption then it would be found that the ratio (C_W-CATAMARAN)/(C_W-MONOHULL)→1 as F_n→0 and as F_n→∞. The ratio at larger F_n will probably be slightly greater than calculated by the authors due to the relative changes in the form factors. However, allowing for the change in running wetted surface area (RWSA) will probably bring the value down again. For a round bilge vessel tested at BMT (FM) Ltd. similar to the C3 monohull, the RWSA at F_n=1 was some 15% greater than the static wetted surface area. For catamarans the increase will be larger. These relative changes in RWSA will reduce the C_T values for the catamarans in relation to the monohulls at higher speeds but will have no effect at low speeds.

Allowing for these changes in RWSA may well result in the C_T-C_{WP} curves matching the new (1+k).C_F curves at higher speeds. If so then the variation in RWSA will be seen to explain the variation of β with L/B that the authors have found, since the change in RWSA with speed for a finer form would be expected to be greater than for a lower L/B ratio form.

Mr D. Bailey (Fellow): If I may return to the derivation of form factor, Dr Gadd is right to point out that the Prohaska method, which depends on very low speed model measurements, could be inappropriate for the high speed form since the flow at the transom at high speed is totally different to that at low speed. However, should the authors feel encouraged to check what I consider to be a high model form factor, the model can be trimmed by the bow at rest such that at low test speeds the flow at the transom is akin to conditions at high speed. Then I think the subsequent measurements will be an acceptable basis for a Prohaska analysis.

The Chairman, Mr A.L. Dorey: The comment made by Dr Wellicome just now about shallow water effects underlines the shame that the big tank at Feltham is no more with us. No doubt most naval architects consider that Feltham was the preserve of the big ship but it was actually the best tank available for high speed ships allowing large models to be run with little if any shallow water effect. All the Vosper Thornycroft fast strike craft were tested there in recent years.

It has been very refreshing to hear the hydrodynamics of high speed craft being debated. It makes one recall the days when it used to happen with respect to more normal merchant ships of slow speed and people exchanged experiences about forms and correlation factors. It is very good to find it being debated this afternoon with respect to high speed catamarans; the work reported is extremely interesting and will be very valuable.

The forms which have been used reminded one a bit of destroyer forms. They are very long thin ships and because stability of an individual hull is not an issue and because frictional resistance is large and wavemaking low, would it perhaps be better to use semi-circular sections as far as possible?

In that connection, I would also like to emphasise the importance of what a previous speaker, Mr Dinham-Peren, said; he was talking about the wetted surface at speed. Has the wetted surface on the models been corrected for speed, i.e. did you allow for the change in wetted surface as the ship goes faster? A number of tanks do this, including BMT I understand. It is an important point to establish, and perhaps the authors could say whether they did or did not make the correction.

The Chairman then proposed a vote of thanks to the authors which was carried with acclamation.

WRITTEN DISCUSSION

Mr A. Millward, M.Sc., Ph.D (Fellow): The authors are to be congratulated on a very interesting and extensive contribution to the knowledge on catamarans. It may be helpful to comment that the authors' conclusion that the interference effects between the two hulls of the catamaran diminishes rapidly with separation can be confirmed from some earlier work on a high speed displacement hull (Model 100A of the NPL series) near a wall. This earlier work, which included both experiments and theory (Refs. 10 and 11), was concerned with the resistance of a fast round bilge displacement hull near a wall in deep and shallow water at distances from the wall of b/L=0.35, 0.58 and 0.81 where b is the distance of the hull centre line from the wall and L is the static waterline length of the hull. This can be taken as equivalent to a catamaran separation distance (S/L) of 0.7, 1.16 and 1.62 so that the results of the experiments extend the range of the present paper to wider separations (although during the experiments in terms of the actual distance from the wall the model was alarmingly close!). These wall results confirm the present work that for separations greater than about 0.5 the interference effect between the hulls is becoming small although even at a separation of 0.7 it can be detected.

It is interesting to compare the authors' values for the form factor for the various hulls in the present paper with some values for two round bilge hulls obtained in the course of some work (Ref. 12) on the effect of shallow water on form factor. The results were obtained by the conventional Prohaska method which involved measurements at low speeds but care was taken to exclude data where extensive laminar flow may have been present on the models which had a waterline length of just under 4 metres. The form factors obtained should therefore be applicable to the lower part of the speed range, below a Froude number of 0.4 approximately, where the transom is still wetted. The values of the form factor are shown in Fig. 23 together with the authors' results when plotted against length to beam ratio (L/B). It can be seen that the value for Model A is much lower than the present results although the value for Model B is much closer. However, it should be noted that Model B had to be tested with appendages present since the tests were carried out on a range of available models and it was not permitted to remove the appendages. In terms of the original experiments, this was not important since the purpose was to determine the additional effect of shallow water but it does mean that for comparison with the present work the form factor of the bare hull of Model B would be considerably lower and therefore more consistent with Model A. The authors' comments would be welcomed.

Finally, the measurements of viscous resistance by the wake survey are very interesting and it would be helpful to know whether the authors encountered any problems with pitot tube measurements near the water surface requiring a correction on the lines of the correction needed near a wall.

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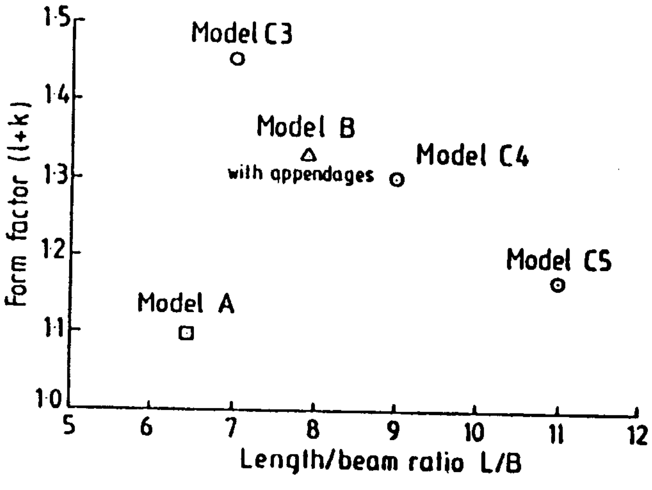

Fig. 23. A Comparison of the Form Factor of Several Round Bilge Displacement Hulls

Mr R.L. Townsin, B.Sc., Ph.D. (Fellow): The authors propose that β should be kept constant across the speed range for practical purposes and no doubt that is sensible with the present state of the art. Figs. 3 to 10 show C_T - C_{WP} not maintaining a constant percentage above C_F. Insofar as C_T - C_{WP} can be interpreted as C_V this suggests a major variation in β with speed; however the authors tell us that the hump in C_T - C_{WP} at about F_n=0.45 is due to wave breaking and transom effects so that the evidence for constancy of form factor lies at F_n about 0.6 up to 1.0. Does this mean that there are no breaking waves and transom effects at the top end of the speed range?

As far as extrapolation of model results is concerned, an assumption of constant β will imply that the breaking wave resistance and transom effects are to be counted as part of the wave resistance. However, the substantial hump in the total resistance curve at F_n about 0.5, just where the constancy of β might be in question, shows that this would not be a design speed in any case.

Professor G. Trincas: I am indebted to the authors for publishing an impressive amount of experimental, analytical and numerical work related to the primary principles of multihull hydrodynamics. My gratitude is even greater after reading the obscure reply of the ITTC Powering Committee to the discussion by Dr Molland on catamaran resistance prediction [13]. The comments and criticisms I am obliged to make probably arise from the limited information given in the paper about the theory, assumptions and procedures used to organise and analyse the experiments.

First of all, a set of questions. After comparing the scatter between the values of the experimental and theoretical wave resistance curves in Figs. 19a and 19b, I should appreciate to receive from the authors a brief summary of their physical and mathematical modelling of the catamaran resistance phenomenon. I suspect that the selection of record length of wave profiles on selected longitudinal cuts is not 'optimal'. Which criterion was selected by the authors? Doliner et al [14] show that the proper criterion for a single longitudinal cut has to satisfy the following condition:

$$\frac{f_o}{B} \geq 2\sqrt{t_{Mmax}} \qquad (3)$$

where f_o is the record length in a single measurement plane, B is the tank breadth, and t_{Mmax} is the normalised y-component wave number given by

$$t_{Mmax} = tg\theta_{Mmax}\sqrt{1 + tg^2\theta_{Mmax}} \qquad (4)$$

Here Mmax is the highest harmonic of the finite spectrum of the wave number and θ_{Mmax} is the maximum propagation angle of component wave trains. As this condition is very restrictive for real experimental situations, the measurements are usually performed in several longitudinal cuts; nonetheless, this criterion must be considered as a necessarily stringent guideline when organising experiments for wave pattern analysis of such a complicated phenomenon as the one under consideration. What value of θ_{Mmax} is sufficient to capture the whole energy content of the waves yielded by a catamaran? Is it about 70 degrees as required for monohulls? Moreover, does the mathematical model include the hydrostatic component of wave resistance and the one due to the transom stern?

My second point is related to the first and concerns the complex function introduced to define the spectrum of free waves in the far field. It is well known that the free surface is obtained by integrating the conjugated Kočin's functions in terms of propagation angles and local wave numbers. In the common experimental situation of a monohull, where symmetry is valid for both the hull and its position in the tank, only even functions are included in expressions for the Fourier transform to define the harmonic amplitudes of the wave elevations. Have the authors also included odd functions in the corresponding expressions? I cannot imagine another way to take into account the asymmetry of the wave trains yielded by the demihulls of catamarans.

The third comment concerns future investigations from the designer's viewpoint. In the final recommendation, the authors want to consider C_p and B/T as primary parameters in further systematic studies. I should like to mention that these quantites may be not so important for interference effects between the demihulls because they are primarily integral parameters affecting the resistance of monohull configurations, whereas systematic variations of S/B and S/T ratios should be more fruitful to give a deeper understanding of this phenomenon. Of course, this idea of mine has to be supported by experimental investigations and sensitivity analyses I am currently planning.

Coming to criticisms, the diagrams in Figs. 7a to 10d show a phase shift between the total resistance (C_T) and viscous resistance (C_T - C_{WP}) coefficients. This physical inconsistency appears also in Figs. 3 to 6 for the resistance components of monohulls. In my opinion, this shift is probably a consequence of the fact that viscous effects due to the rotational wake are not included in the mathematical model when analysing the apparent wave resistance.

Before closing, a last criticism about the authors' comment on Fig. 11. The statement 'the total viscous resistance is seen to be higher than the demihull in isolation, indicating the presence of viscous interference' is not convincing and does not explain why the value of C_V is so high at Fn=0.50. Reported wake contours show that the free surface position stands around zero mean level for Fn=0.35, while it is higher and lower for Fn=0.50 and Fn=0.75 respectively, without satisfying the continuity principle in the wake area. In order to calculate the viscous resistance, one can apply Wehausen's or modified Landweber's formulae [15]. In any case, the wake area has to be defined very correctly. For surface bodies, it has to take into account the wave elevations in the wake domain and has to have a transverse extension such as to incude Kelvin's angle. Figs. 11a, 11b and 11c seem to contradict Bernoulli's law governing the flow in the wake area plane and the boundary conditions on the free surface, thus calling into question the values obtained. Moreover, as the authors apply the wake analysis method of Melvill Jones, it is doubtful if the total viscous resistance coefficients include the wavemaking viscosity effect.

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Mr J. Kecsmar (Junior Member): I would like to thank the authors for an extremely enlightening, and well thought out paper. The conclusions and recommendations are well noted, and will be of great help to designers of high speed displacement catamarans such as myself.

Would the authors please elaborated on Table II, Derived form factors for the models in monohull configuration. They have stated in Section 7 that an estimation of total catamaran resistance may be employed using Figs. 12 to 14 and the form factor for a hull similar to those tested. However, the hull forms presented appear to be almost identical, yet have appreciably different form factor values.

How did the authors arrive at these particular figures, hence enabling one to interpolate for a 'similar' form with confidence? (I assume that the form factor has nothing to do with the form factor associated with the 'Hughes Friction Line', which is a pure friction line, unlike the ITTC 1957 friction line).

Mr K.R. Suhrbier, Dipl.Ing. (Fellow): The authors present a study of the complex problems of resistance components of catamarans, a type of craft which in recent years has attracted a great deal of interest.

In their attempt to improve the understanding of the resistance characteristics involved, the authors also addressed the subject of form factors and their determination. I would like to restrict my discussion to these matters; both are of wider interest for extrapolation procedures for various types of high-speed craft. The data for the NPL monohull forms attracted my particular interest since it is generally assumed that - because of various problems (i.e. change of wetted area, trim, transom stern, etc.) - it is almost impossible or at least difficult to determine meaningful form factors. Also, k is generally considered to be small for most fast craft. As recently recommended by two ITTC Committees, the High Speed Marine Vehicle Committee and the Powering Performance Committee (Refs. 16 and 17), current procedures do not include the use of form factors for high-speed vessels; for the time being k=0 is suggested for (routine) predictions.

It is stated in the paper that 'appreciable viscous form effects' have been found, and the form factors are indeed higher than might be expected, namely 1.17...1.45 for the relatively slender NPL type models C3, C4 and C5. I would therefore like briefly to comment on this.

First some more general points: in discussions at the ITTC, questions are (sometimes) raised as to the general validity of the form factor approaches; other arguments are related to the derivation(s) of 1 + k, although there is, of course, no doubt that velocity form effects and form influences on the viscous component are relevant, and these must be addressed. However, as shown they are not always easy to determine with the necessary accuracy. There can be problems regarding their application for extrapolations (based on flat plate frictional resistance, $C_V=(1 + k)\ C_F$), if contributions are involved which should really be scaled according to Froude's law. (It may just be mentioned that the ITTC 1957 formulation is of course a correlation line and not really a flat plate friction line; it contains some form effect, see Ref. 18).

Secondly, with reference to the approach adopted by the authors, it has obviously been assumed that the viscous component C_V can be determined from C_T - C_{WP} and that wave breaking contributions (including transom stern effects, etc.) are negligible at high Froude numbers. I do not believe that these assumptions are justified and therefore conclude that these are the reasons for the high form factor values obtained.

They, or others derived in a similar way, would lead to under-prediction of powers required (e.g. by about 10% for a 'similar' form and 1 + k of, say, 1.4...1.5).

It may perhaps also be of general interest that a somewhat similar study but different approach for the evaluation of form factors was reported in Ref. 16 and also in more detail in a recent publication by Tanaka et al, (Ref. 19).

I very much hope that the authors will be able to continue their research in this field and I am certainly looking forward to further results.

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Dr H. Tanaka: I believe this paper has many important subjects that include suggestive ideas for hull form design of high-speed catamarans. In order to increase the practical interest, please give me your opinion on the following questions:

(1) When discussing the performance of catamaran hull forms, the study of asymmetrical flow around each demihull is important. Miyazawa (Ref. 20) showed that the asymmetrical flow realises a different flow velocity, draft and wetted surface area between both sides of the demihulls for low speed catamarans. Do you have any comment, even for high-speed catamarans, as to how asymmetrical flow may play an important role in hull form design?

(2) It seems different from our experience, Refs. 16 and 19, that the form factor keeps a constant value during a wide range of F_n=0.1 to 1.0. Although k is difficult to determine at arbitrary F_n, k in high-speed conditions should alter in value with F_n, the main reasons being due to alterations in transom resistance, trim and sinkage.

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AUTHORS' REPLY

Professor Burcher raises the question of wave or surface distortion between the hulls. During the experiments, high waves and apparent wave breaking between the hulls were observed for a certain range of speeds and separations. As the bow waves of each demihull meet on the centreline of the catamaran, they form two or three wave cusps which move aftward with increasing speed and/or widening hull separation. At a critical speed range, the first cusp reaches an unstable height and starts to break with increasing speed. In some cases a water jet formation is also observed. Similar, but smaller in magnitude, wave breaking is observed at the stern. Both wave breaking effects are most critical at about the hump speed, and disappear rapidly above this speed.

Catamarans with asymmetric demihulls can be a difficult task for tank testing. The most sensible approach as suggested by

Professor Burcher, is to use very wide spacing in order to define the non-interfering case. However, experimental and theoretical investigations (for example Refs. 10 and 11) have shown that separation to length ratio must be over about 1.5 to reach the non-interfering case. If the same rule is applied to the tank wall interference, tank width must be over 3L and we suspect that this is not the case for most catamaran experiments. This effectively leaves the only choice as experiments on asymmetric demihulls tested as monohulls to define the interactions. It is believed that systematic experimental data are needed to establish the interactions on asymmetric hulls and to understand the relation between symmetric and asymmetric hulls.

We would like to endorse Mr Bailey's comments on the need for full scale investigation for the confirmation of the test techniques used for this kind of craft. We have a strong desire to pursue such cooperation with catamaran builders and operators to achieve this goal.

We would also agree with Mr Bailey's comment on the importance of determining form factor accurately. However, there are two distinct methods of form factor determination. Although the first method by Prohaska is an efficient and quite accurate way of obtaining form factor for conventional ships operating below the hump speed ($Fn < 0.4$), the effect of a transom stem, running wet or clear of water, makes the use of the Prohaska method inappropriate for high speed craft. Use of a model trimmed by the bow at rest to clear the transom of water at low speeds will introduce even more complexities. The trimmed model and actual running model will have about 8 degrees of trim difference at $Fn=0.7$ leading to a significantly different hull form. It is accepted that the alternative method for deriving form factor, using total resistance and wave pattern measurements as advocated in the paper, suffers from the exclusion from the wave resistance of spray drag and wave breaking resistance. However, as this form factor can be obtained at higher speeds, it is considered that it presents the most feasible and practical approach to the problem and should be pursued further.

Regarding Reynolds Number, the lowest value quoted in the paper corresponds to $Fn=0.1$ which is of little practical importance. It is believed that values upwards of $Rn=1.5x10^6$ (corresponding to $Fn=0.3$) are reliable for practical purposes.

Mr Bailey suggests that a form factor of 1.45 is too high for model C3, indicating possible errors in the resistance results for that model. The reasons for the higher trim values for this model compared with the similar model in Ref. 7 are unclear. A different towing point may well be the cause. However, what is not in doubt is the measured total resistance for model C3, values for which agree very closely with predictions from Ref. 7. Further, the wave pattern resistance measured for model C3 relates closely over much of the speed range to that derived for a model having the same hull form (although with different B/T) reported in Ref. 21.

It is therefore considered that it is not the measured values of total and wave pattern resistance which are in doubt so much as the possible interpretation of these data for the derivation of suitable form factors. To begin with, the interpreted values of form factor could be a little high. This can be seen from Figs. 4, 5 and 6, if an underlying envelope under the wave pattern results had been strictly adhered to. A value as low as 1.35 for model C3 can easily be interpreted. Further, the exclusion of spray drag and wave breaking from the measured wave pattern drag further modifies the current interpretation. However, as wave breaking and spray effects were small for these hull forms at higher speeds, it is believed that these aspects would not have a significant effect.

We would therefore concede that the form factors could be lower than those put forward in the paper (perhaps as low as 1.30 for model C3) depending on the interpretation of the data, but we would argue that they are clearly not 1.0. The viscous traverse measurements, whilst not being of a high order of accuracy, do offer broad support for this argument.

Dr Gadd points out that the interference between Froude Number and Reynolds Number dependent resistance components was not taken into account for the high speed range at which form factors were derived. Although wave breaking losses specially originating from the transom stern are important at lower speeds, flow generated by models C3, C4, C5 was sufficiently clean at the transom at higher speeds. In addition, there was negligible spray formation at higher speeds for these models. Hence the first assumption of independence of wave resistance and viscous resistance was felt to be acceptable for practical applications. Introduction of interference factors β and τ follows the practice of current methods. Dr Gadd makes the point that if the wave breaking effects (including those on the centreline) are larger for the catamaran than for the monohull then this casts doubt on the use of β. As mentioned in our reply to Professor Burcher, for the catamaran case there is significant centreline wave interference/breaking at both the bow and stem, particularly at about hump speed, but which disappears rapidly above this speed. We therefore believe that β is broadly representative of the increase in viscous drag resulting from viscous interference effects although, as mentioned earlier in our reply to Mr Bailey, alternative interpretation of the data might lead to some (relatively small) modifications to the form and interference factors actually employed. This topic is expanded a little further later in our reply to Mr Dinham-Peren.

It is difficult to quote an exact speed at which the flow separates from the transom stem. However, it usually occurred at about $Fn = 0.3$ to 0.45 for the current experiments which does broadly correlate with the speeds at which the $C_T - C_{WP}$ curves diverge markedly from the C_T curves.

Mr Stinton raises the question of splitting a monohull along the centreline, hence forming a catamaran with two flat walls in the tunnel side. A split hull or fully asymmetric hull has been tested on a number of occasions e.g. Ref. 4 includes such a hull form. Although the interference effects are less pronounced than for symmetric demihulls due to the inner flat walls, (with less interference particularly at about the main hump speed), higher drag in isolation associated with bigger wetted surface and higher induced drag than the equivalent symmetric demihull appear as disadvantages of this form. Hence this form may be utilised for catamarans operating at about the hump speed. However, as mentioned earlier there is need for more information on the characteristics of this form.

Dr Wellicome's encouraging discussions over the time this research was conducted are appreciated. We would agree with his statement that the scaling of total resistance minus wave pattern resistance and frictional resistance has not been solved exclusively and full scale results are urgently required.

The shallow water effects and finite width effects are important features of high speed hull tank testing which often cannot be avoided with current tank dimensions. Depth Froude Number for the hulls tested was up to 0.98 for model C2 and 0.93 for models C3, C4 and C5, hence these models were operating at subcritical speeds. Theoretical calculations were carried out based on thin ship theory, including wave interference between the demihulls, to determine these effects. These calculations showed that shallow water effects on wave resistance are less than 2% of wave drag below $Fn=0.9$ (Ref. 8). As the project was aimed at speeds of $Fn=0.6$ to 0.9 and at these speeds the shallow water error was typically less than 1% of the total resistance, no corrections were applied. Calculated tank wall effects for the maximum separation catamaran were also less than 1% of wave drag. Therefore shallow water and finite tank width corrections were not considered necessary below $Fn=0.9$ for this work. A correction above $Fn=0.9$ may be necessary when using the model results for full scale extrapolation.

It must also be mentioned that the wave pattern analysis used to derive form factors through $(C_T-C_{WP})/C_F$ does take shallow water and the finite width channel into account. As these interference effects on frictional resistance are negligible if existent (as model cross section area to tank cross section area ratio is 0.0044 at most) the form factor obtained will be free of shallow water and finite width effects for all the speeds. If a correction is applied, it will be applied to wave resistance only and at speeds above Fn=0.9. More work is being planned for the establishment of shallow water and finite width corrections for multihull vessels.

Mr Dinham-Peren suggests that the model results are likely to be affected by blockage. Firstly, model cross section area to tank cross section area is only 0.0044 for the biggest catamaran which would generally be accepted as having a negligible influence. Secondly, as mentioned earlier, shallow water effects are estimated to be less than 2% below Fn=0.9 and tank wall effects less than 1%. For the biggest separation, model tank side distance to model length ratio was 0.722. Results in Refs. 10 and 11 indicate that this is likely to yield negligible interference for practical purposes.

We wish to make a number of points in reply to Mr Dinham-Peren's comments on derived form and interference factors. Contrary to Mr Dinham-Peren's belief, we have no doubt that there is a viscous interference occurring between the catamaran hulls. Further historical evidence can be derived from the experimental results presented in Ref. 20 for Fn=0.156 and Ref. 22 for Fn=0.18 which indicate that catamarans show substantially higher resistance than twice that of the monohulls, even at these low speeds where wave interactions are negligible, therefore indicating viscous interactions. Additionally, flow visualisation experiments (Ref. 3) at NPL (now BMT) on a catamaran model indicated a change of flow lines and pressure field, hence some form of viscous interaction.

Some doubts have been expressed by other contributors as to the size of the interference and we would concede that alternative interpretations of the data could lead to slightly lower values than those put forward in the present paper. On a similar note, Mr Dinham-Peren is correct in pointing out in Fig. 21 that β should tend to 1.0 as L/S tends to 0, although not necessarily linearly. This should also apply to Fig. 13 in the paper where β should tend to 1.0 for infinite S/B. We were aware of this but chose to leave the curves as published. Slight manipulation of the C_T-C_{WP} curves, particularly for S/L=0.5, could have led to the β values decreasing more rapidly with increase in S/B. We were however attempting to apply the same judgements across the S/L values (particularly at the practically applied S/L values of 0.3-0.4) and the ensuing values results in the oddity to which Mr Dinham-Peren refers.

Regarding Mr Dinham-Peren's interpretation of the low speed results, we were very concerned about the accuracy of these data. The poor accuracy at very low speeds originates mainly from the low values of measured total drag, being typically less than 2.5N for Fn < 0.3, which was difficult to measure accurately by the current means. Thus the diagrams show the existence of a relatively large scatter at very low speeds. Hence it was considered inappropriate to derive form or interference factors from this low speed range and this is why no conclusions were drawn from the low speed results.

Mr Dinham-Peren assumes the running wetted surface area to be larger for the catamaran than the monohull at high speeds. However, the results indicate that the sinkage of the catamaran is less than the monohull while running trim is roughly equal for Fn > 0.6 as shown in Figs. 15a to 18b. This reduces the running wetted area on catamarans by supplying higher lift and, as such, the difference hardly affects the conclusions. The difference between the monohull and catamaran running wetted area was found to be within 2% of static wetted area at higher speeds. Taking into account also the difficulties of measuring the wetted surface accurately on the inboard tunnel side, and bearing in mind the presentation of the monohull data in Ref. 7, no corrections were applied for the wetted area change.

To the Chairman, Mr Dorey, we would answer that the use of semi-circular forms is favoured in sailing catamarans in which viscous resistance is the prime component. However, there are not any powered catamarans with semi-circular sections to our knowledge. An optimisation of viscous resistance (e.g. wetted surface), and wave resistance including interference effects would have to be carried out at the preliminary catamaran design stage in order to determine the usefulness of semi-circular sections.

The results were not corrected to the running wetted surface and the reasons for this approach are given in our reply to Mr Dinham-Peren. Generally, the wetted surface increase was found to be up to 8% at high speeds for model C2.

We would like to thank Dr Millward for providing interference factors for higher separations, noting that they fit in with the trends of the present work. In Fig. 23 Dr Millward presents a comparison of monohull form factors, noting that the naked model A has a much lower value than those for the (naked) hulls of the current work. We would refer Dr Millward to our reply to Mr Bailey in which we express some doubts over the use of the Prohaska method for transom sterned vessels at low speed and the dependence of the magnitude of the form factors of the current work on the interpretation of the data. Bearing in mind these qualifications, there would still appear to be some differences which we are at present unable to explain.

The authors do not fully understand Dr Millward's question regarding the pitot tube measurements near the water surface. The tubes were calibrated over a range of depths up to the water surface and no problems were encountered.

In reply to Dr Townsin, we assumed that (1+k) and (1+βk) are constant across the speed range (0.3<Fn<0.9) for practical purposes only. Some variation of (1+k) with speed is apparent and its use may result in a better scaling procedure. The separation of wave breaking resistance, transom stern drag and spray drag from total resistance minus wave pattern resistance is not possible with the current state of the art. However, as mentioned in reply to other contributors, spray drag at high speeds is negligible for the round bilge vessels tested due to their slender hullforms, and observations during the experiments confirmed this assumption. Our visual observations also indicated that for round bilge hulls, wave breaking is very low in the high speed range compared with the low speed range. Although this may not mean that there are no breaking waves, spray and transom effects present, the errors from this assumption are considered to be relatively small.

Dr Townsin comments that Fn=0.5, where a substantial total resistance hump is located, would not be taken as the design speed. It should, however, be noted that any ship entering harbour or restricted waters needs to slow down and pass through this region, therefore this must be kept in mind at the design stage.

We apologise to Professor Trincas for not presenting the details of the physical and mathematical models. We trust that he will appreciate that they are too long to have been included within the length limitations of the present paper. Full details of the models are, however, included in Ref. 8.

The wave pattern analysis method was developed at Southampton University, and was designed to use multiple longitudinal cuts simultaneously. Details of the analysis are given in Ref. 8. This method was introduced to perform wave pattern analysis in small tanks without truncation errors. Figs. 24a and 24b demonstrate the errors involved in single and multiple cut techniques and it is considered that the criteria given by Doliner will not be critical for the current analysis.

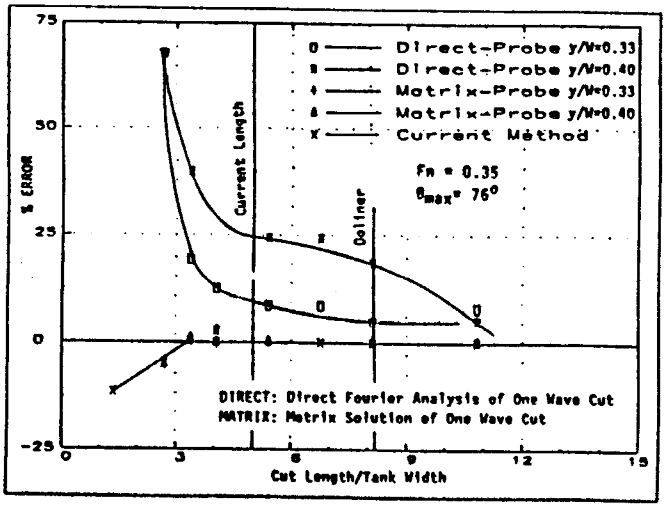

Fig. 24a. Effect of Cut Length on Wave Resistance

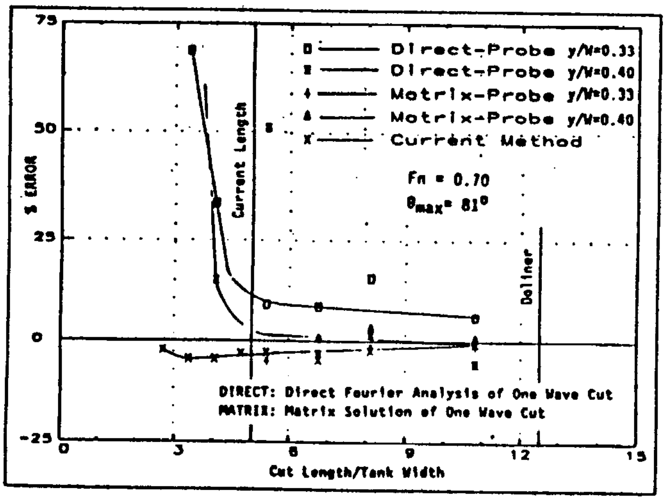

Fig. 24b. Effect of Cut Length on Wave Resistance

The wave pattern analysis was carried out to a maximum wave angle which was not less than 75 degrees. This is assumed to be satisfactory for monohulls and we do not foresee any differences for catamarans.

The mathematical model includes the hydrostatic component as put forward in Ref. 23. Moreover, the running trim and sinkage effects were taken into account by applying the correct trim and sinkage obtained from the experiments.

The wave resistance of a ship model causing asymmetric wave trains relative to the tank centreline must include the odd terms representing the asymmetric trains. In the case of a catamaran symmetric to the tank centreline, the wave pattern will be symmetric, even if the demihulls are asymmetric, as the odd components will be cancelled by the other demihull.

We believe the effect of C_p and particularly B/T should be investigated in order to widen the given method into a larger variation of hull form parameters. These parameters have important effects on the interference factors at different speed ranges as investigated theoretically in Ref. 8. The point made by Professor Trincas on the use of parameters is accepted but we would in any case attempt to arrange the configurations so that the influences of S/B and S/T are detected as by-products of the investigation.

The phase shift observed in Figs. 3 to 10d between the total resistance (C_T) and viscous resistance (C_T-C_{WP}) originates from the exclusion of wave breaking and spray drag from the wave pattern resistance. As the hull encounters the main resistance hump ($0.35<Fn<0.5$) its trim increases very steeply and produces a considerable amount of wave breaking and spray which cannot be measured by wave pattern analysis. This causes a reduced value of C_{WP} in this region which appears as a phase shift in the resistance diagrams.

High values of viscous resistance at about Fn=0.5 are likely to originate from the wave breaking and spray at this speed. The broad agreement between the wake traverse experiments, C_{WT}, and total resistance minus wave pattern resistance, C_T-C_{WP}, confirms that the measured high values should be correct. It is, however, accepted that the accuracy of the wake traverse experiments was not high due to high speeds and relatively small model size, hence limiting their direct use other than for the broad confirmation of total and wave pattern resistance.

In reply to Mr Kecsmar, we would summarise the application of the data as follows. The resistance prediction for a similar hull form catamaran can be made by equation (2) in which β can be chosen from Fig. 13, τ can be interpolated from Fig. 14 and C_F can be calculated from the ITTC 1957 ship-model correlation line. If test data for a monohull are available, k and C_W can be imported, otherwise interpolations from Table II for k and from Fig. 12 for C_W can be carried out. Interpolations can only be made for L/B ratio or $L/\nabla^{1/3}$, since variations of B/T, C_p or other hull form parameters have not been taken into account. Ideally more tests are required on the variation of these parameters, and proposals for such tests are currently in hand. At the moment, we conduct the predictions using the theoretical methods given in Section 6 for 'dissimilar' forms.

Mr Suhrbier, like a number of other contributors, expresses some doubts about the high form factor values presented in the paper. Our replies to the earlier contributors on this topic have indicated that we would not wish to defend these precise values to the limit; however, as mentioned earlier, the wave breaking and spray effects for these hull forms were relatively small at higher speeds (say Fn > 0.6) which suggests that the form factors presented are reasonably close to realistic values and do indicate a significant form effect. The authors appreciate that the use of a form factor of say 1.3 rather than 1.0 will lead to a significantly lower estimate of full scale power, and it is felt that it is only accurately recorded full scale trials which would finally offer a solution to this problem.

Mr Suhrbier mentions the recent work reported in Ref. 19. The models in this case were of hard chine form but one can broadly conclude from Ref. 19 that the models of the present investigation are of adequate size (albeit at about the lower length limit) and that viscous form effect was present in the models of Ref. 19 with form factors (naked hull) of the order of 1.20.

Dr Tanaka raises the question of asymmetrical flow and its role in hull form design. The authors are aware of the work of Ref. 20 and the development of asymmetrical flow in the catamaran case. Asymmetrical flow is likely to lead to induced drag but this contribution has not been identified in the present work. The general shape of the wake contours in Fig. 11 do however confirm that asymmetrical flow occurs also at higher speeds, which suggests that some asymmetrical modifications to the hull form design may be beneficial. The practicality of the present work did, however, restrict our investigation to symmetrical hulls but, as mentioned in our reply to Professor Burcher, investigation of asymmetrical hulls at higher speeds is needed and could prove useful

The results presented in Figs. 3 to 6 do suggest some decrease in form factor with increasing speed (although not as marked as that presented for a different hullform by Dr Tanaka in Refs. 16 and 19). As mentioned in our reply to Dr Townsin, it was mainly for practical reasons that we assumed the form and interference factors to be constant.

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

They would finally add that the lead author, Dr Insel, has recently taken up the appointment as Lecturer in the Faculty of Naval Architecture and Ocean Engineering at Istanbul Technical University, Istanbul, Turkey.

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