CALM WATER POWERING PREDICTIONS FOR HIGH-SPEED CATAMARANS

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ABSTRACT

In recent years, the rapid growth of the high-speed catamaran industry has highlighted problems in the way in which full scale vessel resistance is calculated from model tests. Using the traditional approach the total resistance can be broken down into Froude and Reynolds number dependent components. These are then scaled according to their respective scaling laws.

The common practical method of separating the resistance components is by use of a form factor to estimate the total viscous component. In the case of the catamaran, the form factor will include the interaction effects between the demihulls: changes in the boundary layer due to the modified pressure field around the demihulls; and the influence on frictional resistance of the velocity augmentation between the demihulls.

Of major interest, in the field of high-speed catamarans, is the appropriate magnitude of the form factor and its dependence on hull and operational parameters such as: length: displacement ratio; breadth:draught ratio; separation:length ratio and Froude number. Historically, the choice of form factor for slender catamaran forms has often been close to unity. However, recent research, from a number of independent researchers working in this field, has indicated that this may not be the case and that form factors greater than unity may be appropriate for these vessels.

This paper presents the results of work carried out at the University of Southampton and the Australian Maritime Engineering Co-operative Research Centre which has sought to gain a better understanding of the resistance components of high-speed catamarans and the appropriate form factors to be used for resistance scaling.

1. INTRODUCTION

The high-speed catamaran concept has been growing rapidly for the last ten years; world wide the catamaran concept has been finding greater favour, particularly in the high-speed passenger market. Both designers and investors have shown commitment to the catamaran concept with investment in the latest generation of large catamarans of over 100m in length. Although research in this field has grown significantly in recent years, there is little publicly available information relating to the scaling of model resistance to full scale. The resistance breakdown is especially important for these slender vessels since the Froude number dependent portion of resistance is only a small proportion of the total resistance. This is particularly true at high Froude number and at model scale. This paper reviews current scaling procedures and presents new work in this field with the aim of providing a better understanding of appropriate resistance breakdown and scaling for high-speed catamaran vessels.

Emphasis in the paper is directed at developing a fundamental understanding of the resistance components of high-speed, transom stern vessels, with particular reference to catamarans. At the same time, conclusions relating to form effect on viscous resistance and catamaran viscous interaction are drawn which are aimed at providing practical guidance to the designers of such vessels.

2. RESISTANCE COMPONENTS AND SCALING

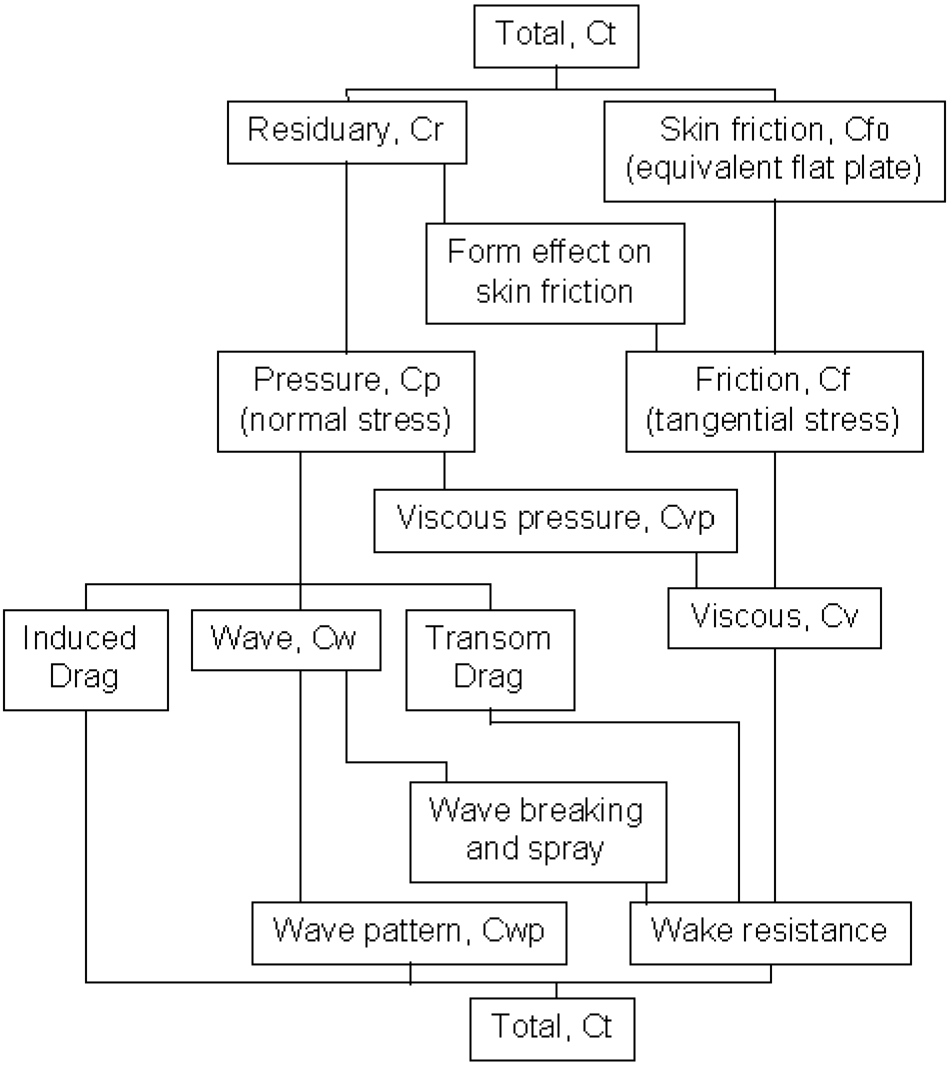

Figure 1: Breakdown of resistance into components.

The resistance of a surface vessel may be broken down into components attributed to different physical processes, which scale according to different scaling laws. Such a breakdown is presented in Figure 1. The resistance of a vessel (neglecting air resistance) is due to shear and normal fluid stresses acting on the vessel's underwater surface. The shear stress component is entirely due to the viscosity of the fluid, whilst the normal stress component may be separated into two major components: wave making, due to the generation of free surface gravity waves (inviscid) and a viscous pressure component caused by the pressure deficit at the stern due to the presence of the boundary layer (viscous). The transom stern presents a special case and this has been included as a pressure drag component, as has induced drag for catamarans.

The standard ITTC practice is to break down the total resistance into viscous resistance (Reynolds number dependent) and wave resistance (Froude number dependent) components. This is described in Equation (1). The wave resistance, R_W, contains the inviscid component and the viscous resistance, R_V, includes the resistance due to shear stress (Friction drag) and the viscous pressure component (discussed above). In practice the viscous resistance is usually estimated using the ITTC-57 correlation line (C_F) together with a suitable form factor (1+k). Here C_F is an approximation for the skin friction of a flat plate, the form factor is used to account for the three dimensional nature of the ship hull. This includes the effect of the hull shape on boundary layer growth and also the viscous pressure drag component. It should be noted that the ITTC-57 correlation line is an empirical fit and that some form effect is included. The wave resistance component is usually derived from model tests or possibly from inviscid computational fluid dynamics (CFD) methods.

$$R_T(F_n, R_e) = R_W(F_n) + R_V(R_e) = R_W(F_n) + (1+k)(F_n)R_F(R_e) \quad (1)$$

A particular problem for catamaran vessels at high-speeds ($F_n > 0.6$) is that, due to their slenderness, the total resistance is dominated by the viscous resistance component. This is highlighted in Figure 2 and Figure 3 which show the relative magnitudes of the different resistance components at model scale. This is unfortunate since the friction is calculated empirically based on the friction of a flat plate and is then modified, in a semi-empirical manner, to obtain the viscous resistance component; the relative magnitude of this component can lead to a lack of precision in the final result.

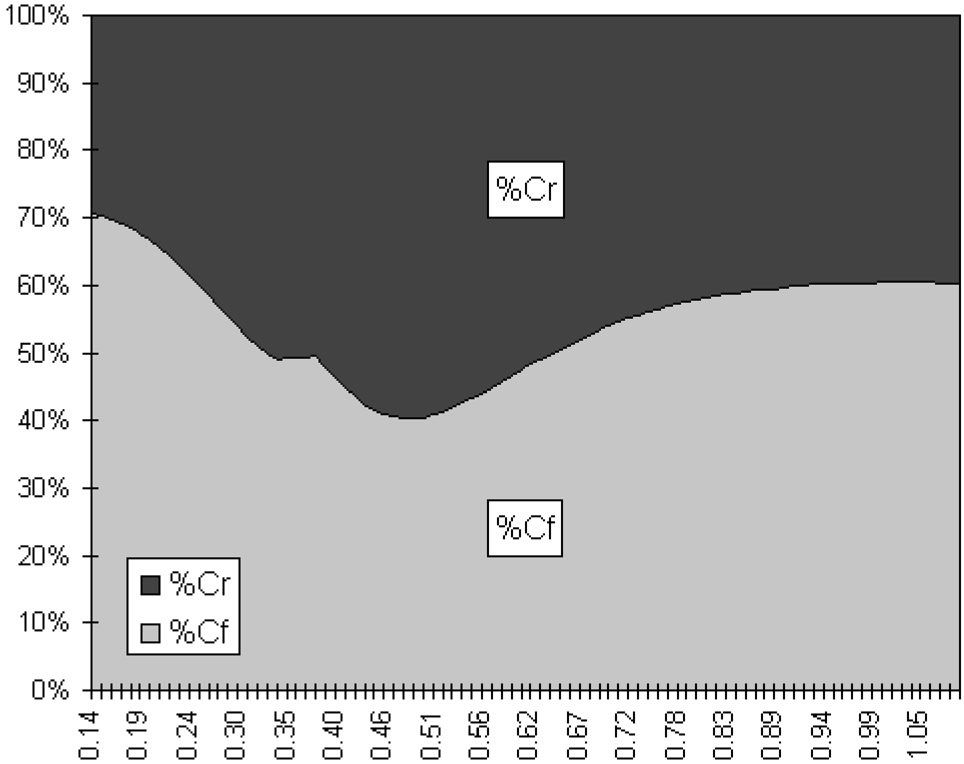

Figure 2: Relative magnitudes of resistance components for typical catamaran hull form using $C_T = C_R + C_F$ breakdown.

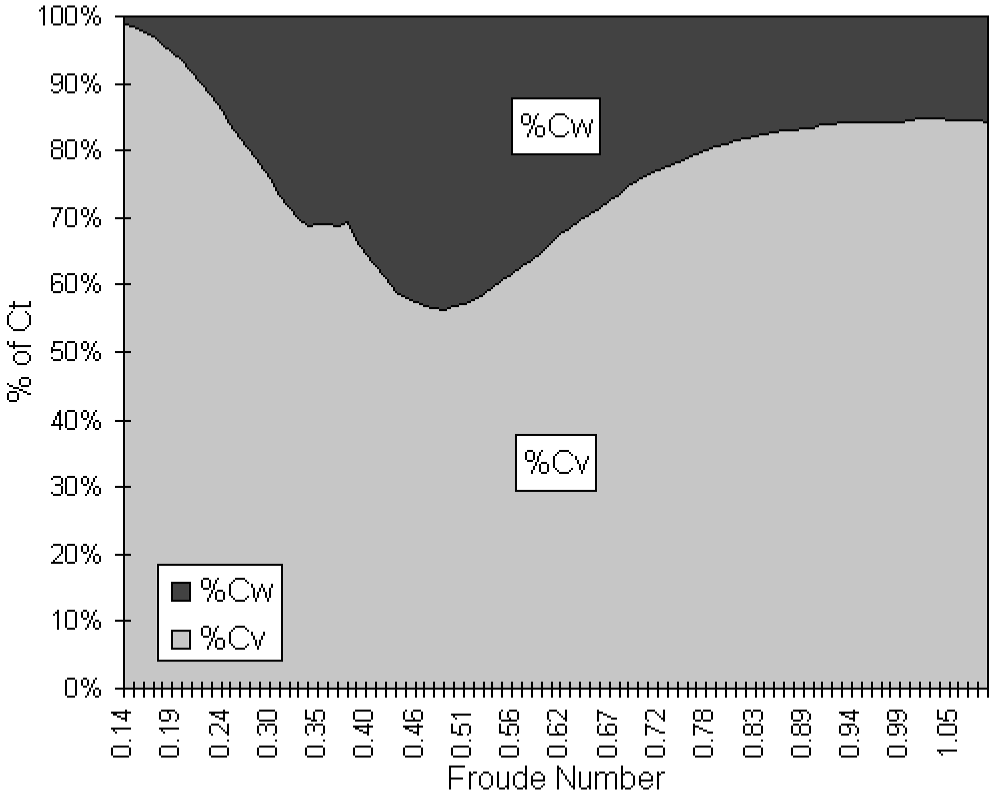

Figure 3: Relative magnitudes of resistance components for typical catamaran hull form using $C_T = C_W + (1+k) C_F$ breakdown.

It is therefore quite clear that the selection of a suitable form factor is critical to accurate extrapolation of model test results to full scale. Whilst it is possible to determine the form factor of a high-speed vessel by a number of alternative methods, it is not readily found during standard model testing procedures.

2.1 Direct measurement of resistance components

A number of researchers have attempted to measure the individual resistance components. Apart from total resistance, it is also possible to measure the viscous resistance and the wave pattern resistance to a reasonable degree of accuracy; from these measurements, the form factor may be derived.

The viscous resistance component may be derived from measurements of the velocity field behind the hull. The transverse extent of the wake survey will determine how much of the viscous component is measured. For slow speed forms, the viscous debris is concentrated in a wake directly astern of the model. However, for high-speed vessels significant viscous debris, probably originating from the spray sheet, may be observed to extend several times the model maximum beam either side of the model centre line. In addition, this component may also be investigated in the wind tunnel.

The wave resistance component may be derived from measurements of the wave pattern using an Eggers (1965) type approach. The form factor may be deduced by subtracting the measured wave pattern resistance from the measured total resistance. However, the assumption implicit in this method is that the other non-viscous components of resistance are negligible (see Figure 1).

2.2 Geosim series - A series of geometricall identical models of increasing length.

Models are tested at different scales and hence Reynolds numbers. Since the viscous resistance is a function of Reynolds number the resistance breakdown may be derived from model tests at the same Froude number but different Reynolds number. This approach was first suggested by Hughes (1954, 1966). This method correlates the resistance of models tested at the same Froude number but different Reynolds number and leads the way to correlation with full scale resistance predictions. This method does not however, lead to a more detailed insight into the physical significance of the resistance components (and the mechanisms by which they are generated) but can be used to determine full scale resistance.

2.3 Slow speed tests

Prohaska's method allows the form factor to be calculated by assuming that, at low speed, the total resistance is described as: $C_T = C_{W0} F_n^x + (1 + k) C_F$ (x is usually 4). This method is widely used for slow speed vessels without immersed transoms. However, its application to transom stern vessels is questionable because of the different flow regime in the transom area. (The flow does not separate from the transom at slow speed as it does at high speed.) Furthermore, with slender hulls, the drag at slow speed is so small as to be difficult to measure accurately.

2.4 Eliminate wave resistance component

Wind tunnel experiments enable direct measurement of the viscous resistance since no free surface waves are generated. Careful consideration of the flow around the transom of the model is required.

2.5 Computational Fluid Dynamics (CFD) methods

CFD techniques, of varying degrees of complexity, may be used to predict various resistance components: Potential codes may be used to derive the pressure resistance due to inviscid flow characteristics (wave pattern resistance). The boundary layer integral method may be used to estimate the boundary layer growth in areas where separation and recirculation do not occur. This method would provide some insight into the pressure form drag. Full Reynolds averaged Navier Stokes (RANS) codes may be used to predict the flow where separation and recirculation occur, thus potentially providing good estimates of form factor; however these methods are extremely computationally intensive.

3. EVALUATION OF RESISTANCE COMPONENTS

Various methods for determining the resistance breakdown have been discussed in the preceding section. Results of various research programmes are presented and discussed in order to provide guidance as to the form factors which are appropriate for high-speed, transom stern vessels. The particular case for catamarans and the viscous interaction effects between the two demihulls are discussed in detail.

3.1 Form factors of fine vessels

It has been shown that apparent form effects may be observed for very slender hull forms such as Wigley (1934, 1942) and rowing eights (Wellicome 1967, Scragg and Nelson 1993). Insel (1990) (Figure 107, p230) compares the results of a number of researchers, for viscous wake measurements of the Wigley hull form. The form factors were found to be approximately 1.10 for $0.25 < F_n < 0.55$. Wellicome gives form factors of 1.09 for a rowing eight racing shell from slow speed tests; Scragg and Nelson also quote similar values. This was a very slender hull form with $L/\nabla^{1/3} = 19$ and L/B = 60.75.

These results indicate that even extremely slender hull forms may have a viscous resistance component which is significantly greater than the frictional resistance of an equivalent flat plate based on the ITTC-57 correlation line.

3.2 Form factors of high-speed transom stern monohulls

The following discussion is based on the work carried out by Tanaka et al. (1990) and Cordier and Dumez (1993) on the 26.4m high-speed, monohull, passenger ferry, *Olive*. Both groups carried out tests at different model scales, measured wave pattern resistance and, in the case of Cordier and Dumez, measured the viscous resistance component. The results of these experiments may be used to determine the form factor of the vessel by the various methods described in Section 2.

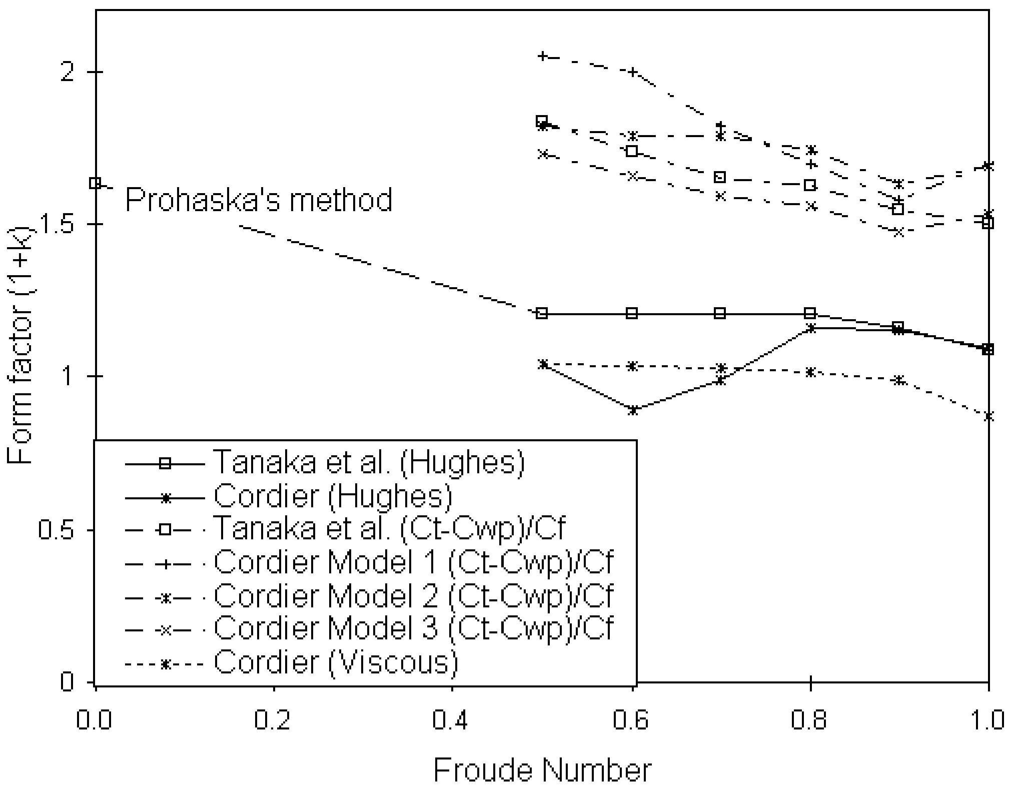

Figure 4: Form factors derived by a variety of methods.

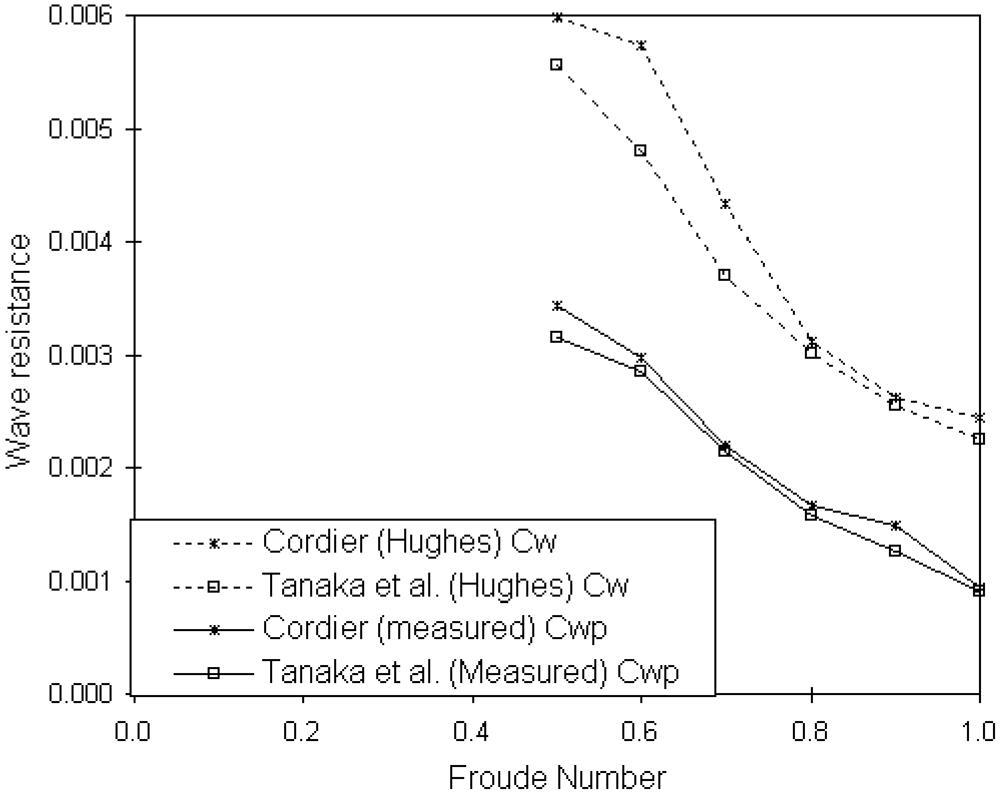

Figure 5: Wave resistance: measurements and extrapolation.

The form factors derived are presented in Figure 4. In addition the wave resistance derived from the wave pattern measurements and Hughes' method are given in Figure 5.

In Figure 4, it may be seen that in all cases the form factors reduce with increasing Froude number. There is also considerable variation depending on the method of analysis: The form factors derived from Cordier and Dumez's viscous wake measurements are the lowest (1.05 to 0.85). The results of Tanaka et al. using Hughes' method are approximately 25% greater (1.30 to 1.09) whilst those based on wave pattern measurements are the greatest, approximately 50% to 100% greater than those obtained by the viscous measurements. The form factor obtained by Prohaska's method from slow speed data shows some correlation with those derived from wave pattern measurements.

It should be noted that all but the largest of Tanaka et al.'s models were tested without turbulence stimulation (at the time, this was standard procedure for the testing of high-speed vessels in Japan); indeed one of the recommendations of the work was that turbulence stimulation was necessary and that suitable stimulators for high-speed vessels should be developed. The models of Cordier and Dumez were tested with turbulence stimulation. The presence of significant laminar flow (due to a lack of turbulence stimulation) would reduce the resistance of the models, particularly the smaller ones. In turn, this would reduce the form factors derived from geosim extrapolation.

The measured wave pattern and viscous resistance components may be added and compared to the measured total resistance. Cordier and Dumez (1993) found good correlation for a slow-speed series 60 hull form but poor correlation for *Olive*. This can be partly attributed to the small transverse extent of the viscous traverse used: Insel (1990) found reasonable correlation between the measured total resistance and the sum of the wave and viscous resistance. In this case, the viscous traverse was sufficiently wide to pick up the momentum deficit thought to originate from the spray sheet re-entering the free surface.

Dumez (1993) makes the comment "Hence, there is an important difference between the two methods of obtaining the viscous resistance (and hence residual resistance) of high-speed vessels and, at present, it is not possible to determine which is the more precise."[1] However, from a full scale extrapolation point of view, it is likely that form factors derived by Hughes' extrapolation will be most accurate. The relatively narrow wake survey made by Cordier and Dumez may have produced an underestimate of the viscous resistance component and hence the form factor, whilst the wave pattern resistance method could over predict the form factors if significant wave resistance is lost in the near field due to wave breaking and spray effects.

Insel (1990) carried out similar experiments, where the wave pattern resistance and viscous resistance were measured in addition to the total resistance. The models used, based on the NPL round bilge series (Bailey 1967), were 1.6m in length and fitted with turbulence stimulation. The viscous wake traverse extended to approximately twice the model beam hence the measured viscous component included areas which may have originated from the spray sheet. The results of these experiments indicated form factors of the order 1.45 to 1.22 for $L/\nabla^{1/3}$ = 6.3 to 9.5, and the sum of the wave pattern and viscous resistance was found to be in broad agreement with the measured total resistance. These form factors were of similar order of magnitude as those obtained from the geosim analyses discussed above and may indicate that the resistance component associated with the spray sheet which is picked up as viscous debris in the wide viscous traverse should be included in the viscous component and scaled according to Reynolds number.

Table 1 summarises the form factors for the different models, however, these comparisons should be treated with caution since the hull forms show some significant differences. *Olive* is a hard chine vessel with more characteristics of a planing vessel than the NPL round bilge forms of models 3b to 6b; it is not clear what effects these differences would have on the form factor, although the chine vessel might be expected to have a lower form factor since is may be considered to be made up of a number of two dimensional plates, whilst the round bilge design is more three dimensional.

Table 1: Comparison of vessel parameters and form factor.

Vessel	$L/\nabla^{1/3}$	L/B	Form factor
Olive	6.5	4.46	1.0 to >1.5
3b mono	6.3	7.0	1.45
4b mono	7.4	9.0	1.30
5b mono	8.5	11.0	1.26
6b mono	9.5	13.1	1.22

It has been shown that the apparent form effect varies considerably with the method of analysis used. It is probable that form factors based on geosim data will be most accurate from a resistance scaling point of view. However, the measurement of individual resistance components is invaluable in the quest for a fundamental understanding of the resistance characteristics of these vessels. It would also appear that the transom has a significant, if not yet fully understood, effect on resistance. It will be shown that the findings for monohulls are pertinent to catamarans, which have the added complications of wave and viscous interactions between the demihulls.

3.3 Form factors of high-speed catamarans

Insel (1990) also carried out viscous measurements for several catamaran forms. Again agreement was found between the total resistance and the sum of the wave pattern and viscous resistance. Form factors for all the demihull spacing tested were found to be considerably higher than those of the monohulls suggesting that viscous interaction effects were present. It is unclear whether the viscous resistance increase is due primarily to modifications of the boundary layer and velocity augment between the demihulls or to additional spray associated with constructive interference of the two wave systems, particularly in the vicinity of the transom.

The catamaran series was extended by Molland et al. (1994, 1996). Measurements of total and wave pattern resistance were made, from which form factors were derived. Evidence to suggest viscous interaction was found in all the catamarans tested. The catamaran configurations were found to have approximately 10% greater form factor than the monohulls. However, no significant variation of viscous interaction with demihull spacing could be detected and the level of viscous interaction remained approximately constant over the range of demihull separations tested. These interaction effects have been studied further using wind tunnel models, the results of which are discussed below.

3.3.1 Wind tunnel tests with ellipsoids

Wind tunnel tests have been carried out (Molland and Utama 1996) in order to isolate the body's viscous drag component and to provide an insight into the viscous interaction between a pair of bodies. A pair of ellipsoids 1.2m in length and 0.2m in diameter were tested in the 2.1m by 1.5m wind tunnel at the University of Southampton. Models were tested at speeds of up to 40m/s, (R_e = 3.2x106). Total drag, sideforce and pressure distribution were measured. Tests were carried out with and without turbulence stimulation strips and at body spacings of S/L=0.27, 0.37, 0.47, 0.57.

The overall drag coefficients and pressure distributions were comparable with earlier published data for single bodies of revolution in isolation. Figure 6, which shows the ratio of twin body viscous drag to single body drag, clearly illustrates a significant viscous interaction between the bodies, and that this interaction is maintained at an approximately constant level up to about S/L=0.5. This trend is further supported by the CFD results (based on two dimensional ellipses) which show the interaction to remain constant up to this point before decreasing at higher S/L values.

It may also be seen that a significant attractive side force is developed between the bodies, particularly at the closer spacing. Cross flow over the bodies, observed during flow visualisation tests, supported these findings. The cross flow would suggest the possibility of induced drag; however, since the sideforce decreases rapidly with increasing separation whilst the drag remains approximately constant, it may be inferred that the total drag does not contain a significant induced drag component.

The levels of interaction were found to increase when turbulence stimulation was provided. The reasons for this are not yet fully understood but may be due to increased boundary layer thickness and are still under investigation. The results showed interactions of the order of 4% without turbulence stimulation; this was increased to 10% with turbulence stimulation.

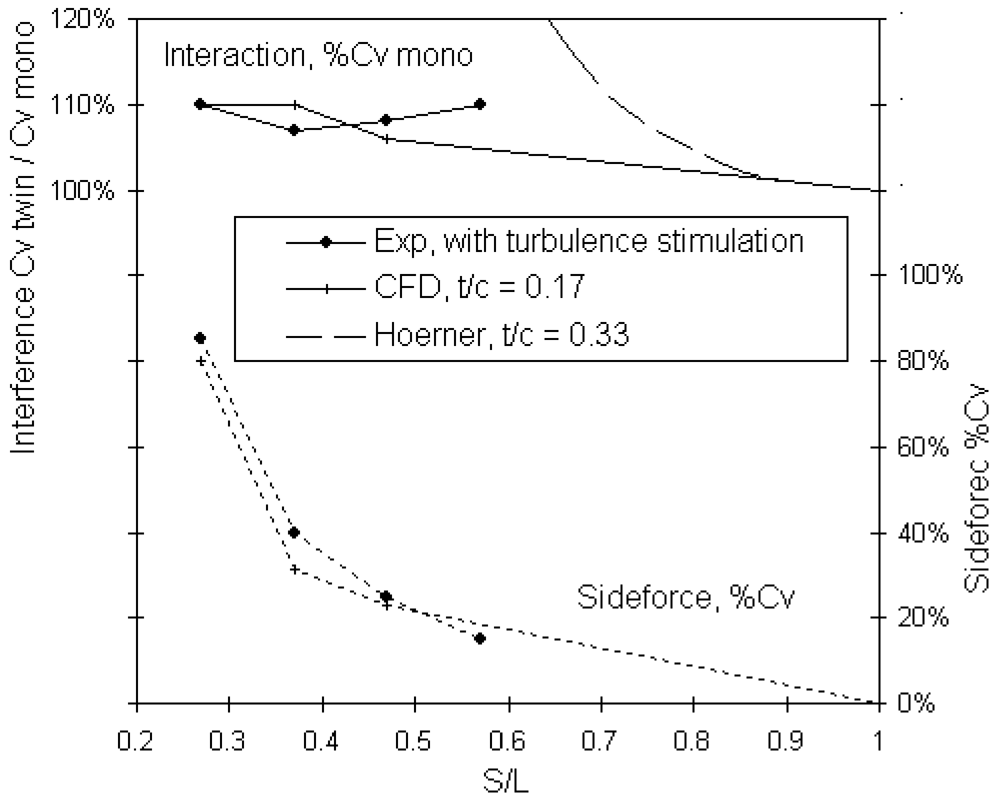

Figure 6: Viscous interaction of a pair of ellipsoids.

3.3.2 Wind tunnel tests with reflex models

This is a technique pioneered by others (Joubert 1970) where the resistance of the hull is measured in a wind tunnel. Obviously in this situation there can be no wave making and all the resistance must be of a viscous nature. An implicit assumption, for the reflex model, is that the waterline is level. For high-speed craft with slender hulls this is a fairly valid assumption.

One of the catamaran demihull shapes tested by Insel and Molland (1992) was made as a reflex model and tested by Armstrong (1995). A fairing was fitted behind the transom to simulate the cavity in the water behind the transom; dimensions were taken from a towing tank model. Turbulence stimulation was provided at the bow. The pressure distribution over the hull was measured at a variety of demihull separations and integrated to determine the total pressure resistance. This value compared well with Insel's towing tank results.

The effect separation was quite small and was difficult to measure accurately because of the interference effects of the model supports. These results have yet to be fully analysed, but show a constant interference effect of about 6% at the closer spacings.

3.3.3 Prohaska's method

Application of Prohaska's method to high-speed transom stern vessels poses several problems which have been discussed in Section 2.3. Tests have been performed by Molland et al. (1995) with the vessel trimmed by the bow to emerge the transom (ie: sufficient bow down trim to raise the transom above the still water line was provided). This method, for transom stern vessels, was originally put forward by Bailey in the discussion of Insel and Molland (1992). Form factors of the order of 1.55 at normal trim and 1.37 with transom emerged were found. These results showed some agreement with the form factor obtained from the total resistance minus wave pattern resistance method (1.44). (Note: this was for a catamaran configuration, for the same hull form in monohull configuration, form factors may be expected to be reduced by approximately 10% for both trim conditions.)

3.3.4 Induced drag

In the case of the catamaran, there is the potential for induced drag to be generated due to the asymmetric flow over the individual demihulls. This aspect has been investigated, using towing tank models, by Couser (1996). As with the wind tunnel results, significant transverse splaying forces were measured (4%-16% C_T), a similar magnitude lift force was generated by the isolated demihull operating at a yaw angle of 0.4 degrees. At this low yaw angle, the induced drag was negligible (approx. 0.3%-0.1% C_T). The sideforce measured in these experiments would have included both viscous and wave effects. In fact the magnitude and direction of the force was found to vary considerably with speed, due to the relative importance of the inward force originating from asymmetric flow over the demihulls and the outward force due to the surface wave systems.

3.3.5 CFD investigations into form effects of high-speed catamaran demihulls

Catamaran hull shapes have been modelled by Armstrong using the commercial CFD package FLUENT. Hull forms including the wind tunnel tested NPL form (Section 3.3.2) and commercially-built forms for which both tank test results and full scale trials data were available, have been modelled. Compared with the wind tunnel results, the numerical predictions of hull pressure distribution showed a good degree of accuracy, although the predicted overall viscous drag was lower than that measured in the wind tunnel, thus resulting in lower apparent form factors (about 1.07 for monohull 5b tested by Molland et al. (1996), for which the form factor obtained from tank tests was 1.26 and 1.19 from wind tunnel tests).

3.4 Full scale results

Table 2 presents the form factors of 14 catamarans derived from tank data and full scale trial measurements. All these craft were powered by waterjets for which the thrust was determined from the vessel speed, shaft revolutions and power. For a number of the vessels, the waterjet thrust was confirmed by pitot rake measurements of the waterjet outlet velocities. The form factors presented in Table 2 have been derived according to Equation (2). In all cases the form factors are greater than unity. The values show some dependence on vessel displacement, length and speed. In all cases, if the true form factors had been unity, the model data would have predicted a trials speed less than that achieved.

$$\frac{C_T\text{model} - C_T\text{ship}}{C_F\text{model} - C_F\text{ship}} = (1+k) \tag{2}$$

Table 2: Form factors derived from full scale trials and model tank data

Hull	Disp.	Speed	Length	Form factor
A	heavy		31.5m	1.45
	light		31.5m	1.40
B	heavy		31.5m	1.45
	light		31.5m	1.45
C	heavy		31.5m	1.36
D	heavy		32.5m	1.30
	light		32.5m	1.12
E	heavy		32.5m	1.38
	light		32.5m	1.16
F	light		40.43m	1.14
G	heavy		61.1m	1.21
H	heavy		61.1m	1.17
I	heavy	low	61.1m	1.20
	heavy	high	61.1m	1.10
J	heavy	low	61.1m	1.19
	heavy	high	61.1m	1.10
	light		61.1m	1.04
K	heavy		61.4m	1.25
	light		61.4m	1.04
L	heavy		61.95m	1.18

	light	61.95m	1.07
M	heavy	61.95m	1.18
	light	61.95m	1.07
N	heavy	61.95m	1.22

3.5 Effect of spray and wave breaking

The wave pattern analysis, described in Section 2.1, used to determine the wave pattern resistance makes the assumption that the waves are linear and that all the energy associated with producing the free surface wave field is transported to the far field. The occurrence of wave breaking in the near field violates these assumptions and hence underestimates the wave resistance component. This, in turn, would lead to an overestimate of the form factor. It is difficult to measure the wave breaking component directly, however a qualitative estimate may be made from visual observations. In the case of the high-speed, transom stern catamarans tested by Molland et al. (1994) little wave breaking was apparent except in the Froude number range $0.4 < F_n < 0.6$. This coincided with the speed range at which the transom started to run clear and a steep 'rooster tail' was observed behind the transom; some wave breaking was also observed for the lower $L/\nabla^{1/3}$ hull forms when tested in catamaran configuration with closely spaced demihulls. The wave breaking occurred at the point where the two bow wave crests met. Viscous debris, thought to be due to these effects has been detected in viscous wake measurements.

Using the simple relationship that wave energy is proportional to the square of the wave height, it is possible to estimate the attenuation of the waves in the far field which must have occurred in order that the wave resistance is equal to the residuary resistance (indicating a unity form factor). This relationship is described in Equation (3). Figure 7 shows this ratio plotted against Froude number for two models in monohull and catamaran configuration. It may be seen that the wave amplitudes would have had to have lost 34% to 41% of their amplitude due to wave breaking by the time they arrived in the far field. This level of wave breaking was not supported by visual observations during the tests.

$$\frac{\zeta_{\text{far field}}}{\zeta_{\text{near field}}} = \sqrt{\frac{C_{WP}}{C_R}} \qquad (3)$$

In addition, given that the wave profiles of the Wigley and the higher $L/\nabla^{1/3}$ NPL hulls were of a similar size, it is unlikely that the differences in form factors between these hulls could be attributed solely to additional wave breaking for the NPL hull forms. It is more likely that the transom has an important rôle to play in the viscous resistance of such vessels.

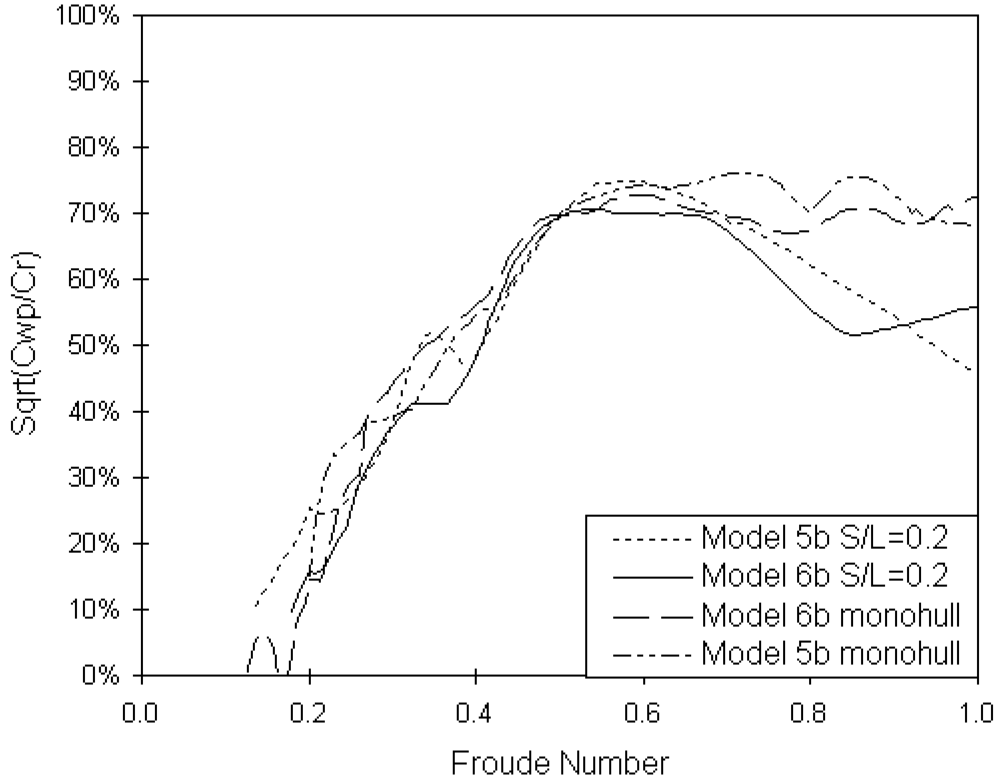

Figure 7: Required attenuation of wave height to achieve unity form factor.

4. TRANSOM EFFECTS

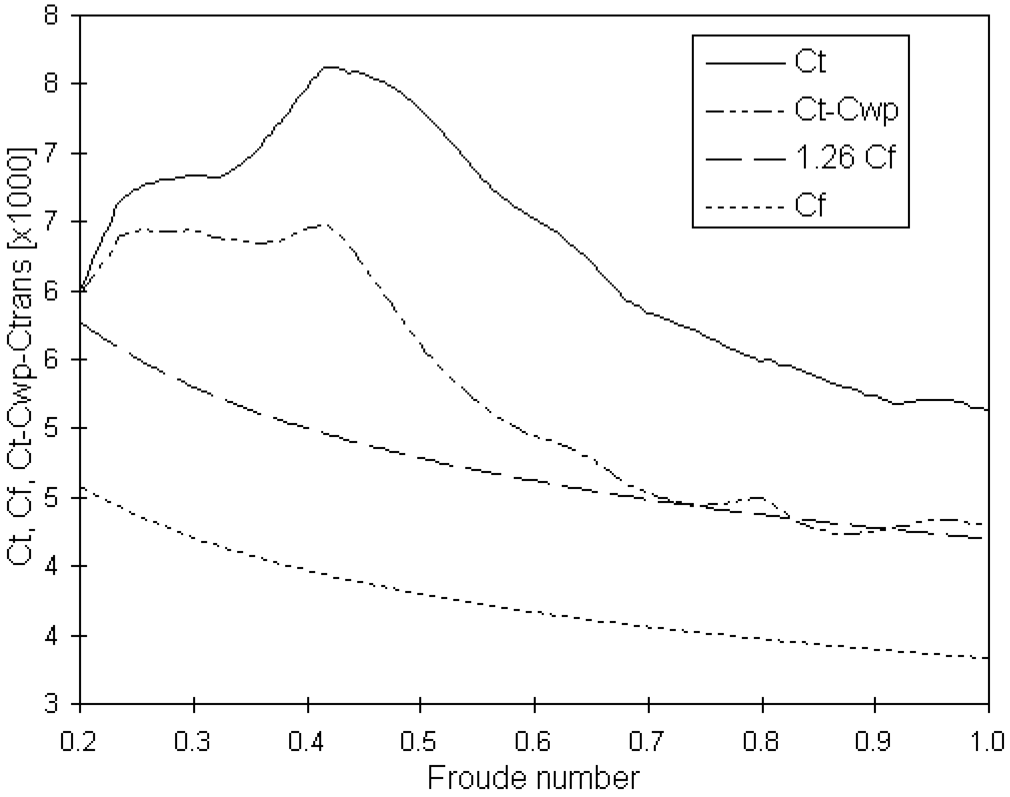

Figure 8: Calculation of form factor from wave pattern resistance measurements.

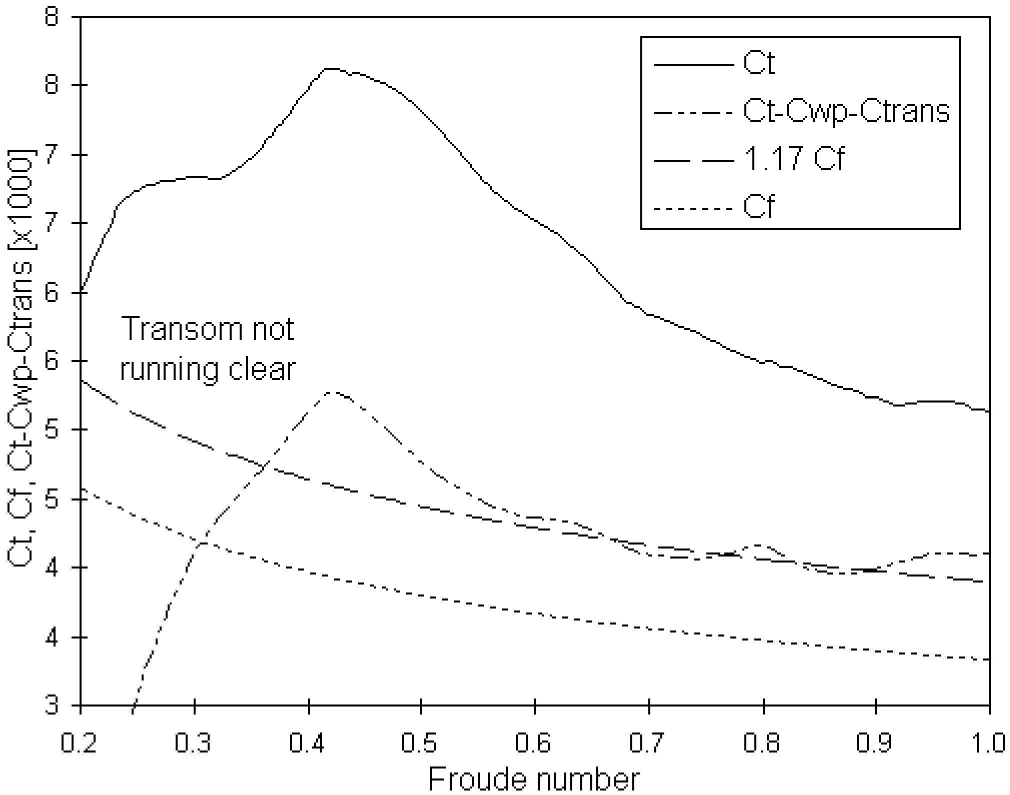

Figure 9: Recalculation of form factor including hydrostatic correction.

A typical resistance breakdown is shown in Figure 8. As has been discussed earlier, the principal problem with calculating form factors from wave pattern measurements is the uncertainty that all the wave resistance component is measured in the wave pattern. For the case of a vessel with a transom stern, it is possible that the large low pressure area directly behind the transom which causes the transom to be at atmospheric rather than stagnation pressure, causes waves (and spray and wave braking) which are not fully transmitted to the far field. If this were the case, the pressure resistance of the vessel (derived from far field wave pattern measurements) would be underestimated. This may be corrected by the addition of a resistance term corresponding to the integration of the hydrostatic pressure forces which would act on the transom were it immersed. This method has been applied to model 5b in monohull configuration, and a new form factor derived from $(1+k)C_F = C_T - C_{WP} - C_{Trans}$. The results of this analysis lead to a reduction of form factor of the order of 7%; from 1.26 to 1.17. It is interesting to note that this is a similar reduction to that found from the transom emerged tests described in Section 3.3.3. Figure 8 and Figure 9 demonstrate the effect of this analysis. It may also be seen that the transom effect considerably reduces the 'missing' resistance component (usually attributed to spray and wave breaking), thus helping to rationalise the differences between the form factors calculated by Cordier and Dumez's viscous measurements and those obtained by other methods.

5. PRACTICAL IMPLICATIONS

This paper has discussed the various physical phenomena which might influence the form factors applicable to round bilge, transom stern, fast craft. It is apparent that there is still a reasonable level of uncertainty in estimating the magnitude of the form factor for such vessels. However, bearing in mind these various issues and the evidence presented in this paper, it is considered that, for practical purposes, plausible form factors can be assembled as shown in Table 3.

These form factors are based on assumed corrections for transom stern effects and, for the catamarans, levels of viscous interaction based on the evidence of wave pattern measurements and wind tunnel tests. Form factors may be assumed to be sensibly constant with Froude number and demihull separation, and the primary geometric parameter has been found to be $L/\nabla^{1/3}$. They also compare reasonably well with the form factors derived from full scale measurements (Table 2).

Whilst there is evidence to suggest that these form factors are in the correct range, it is apparent that they should still be used with caution and compared with existing procedures for practical resistance estimates.

Table 3: Suggested form factors for high-speed, round bilge forms (independent of catamaran demihull separation)

	Form factors	
$L/\nabla^{1/3}$	Monohull	Catamaran
6.3	1.35	1.48
7.4	1.21	1.33
8.5	1.17	1.29
9.5	1.13	1.24

6. CONCLUSIONS

Form factors may be derived by a variety of methods: direct measurement of viscous and/or wave pattern resistance; Prohaska's method from slow speed data, possibly with the transom emerged; Hughes' regression based on geosim data; and full scale thrust measurements. Each method has advantages and disadvantages and although some agreement may be found, the differences in the derived form factors can be quite high. At present it is not possible to determine, with certainty, which method provides the most accurate estimate of form factor.

It has been shown that there is a significant body of experimental evidence to suggest that the viscous resistance of high-speed, transom stern vessels is substantially greater than that of an equivalent flat plate. Indeed, form effects of as much as 10% have been noted for slender vessels without transom sterns. Further, it is suggested that appropriate form factors for fast, transom stern vessels are significantly greater than unity. These findings have been supported by the results of full scale trials also presented in this paper.

Apparent viscous interaction for catamaran forms has been noted during tank tests, and this has been supported by wind tunnel investigations. The levels of interaction appear to be of the order of 10% of the viscous resistance of the isolated demihull. Another interesting feature is that the interaction appears to stay at a sensibly constant value for practical ranges of body separation up to S/L = 0.5.

One of the main arguments put forward against the high form effects suggested here, is the presence of substantial wave breaking and spray resistance. A rudimentary analysis has shown that, while some apparent form effect may be attributed to these phenomena, it is unlikely that all the form effect deficit can be recovered in this way and in any case observations of full size vessels suggests that wave breaking and spray effects are small.

An alternative resistance breakdown and scaling procedure, which deals with the effect of the transom directly, has been put forward. This method has shown promise in that it has helped to rationalise the form factors derived by the different methods.

Although only mentioned briefly, the use of CFD can provide a useful insight, particularly of the effects of viscous and wave interaction between catamaran demihulls.

It is apparent there is a need for further fundamental research in this field, particularly with regard to the effect of the transom and the interaction effects between the catamaran demihulls. Further detailed full scale measurements, including accurate resistance and wave pattern measurements are also necessary for validation purposes.

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Footnotes

1 Translated from the French: "Il y a donc un écart important entre ces deux méthodes d'obtention de la résistance visquese (et donc la résistance résiduelle) de navires rapides sans qu'il soit possible, pour l'instant, de déterminer laquelle des deux est la plus précise."