ON THE MACRO HYDRODYNAMIC DESIGN OF HIGHLY EFFICIENT MEDIUM-SPEED CATAMARANS WITH MINIMUM RESISTANCE

(DOI No: 10.3940/rina.ijme.2012.a3.234)

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SUMMARY

A new class of fuel-efficient and environmentally friendly twin-hull vessels is currently under development. Compared to high-speed catamarans, a significant reduction in speed combined with an increase in deadweight tonnes will lead to a highly efficient medium-speed catamaran design. Recently-built conventional and high-speed ferries are compared to each other in terms of length, speed, deadweight and transport efficiency to classify the new design. The goal of this study is to find a preliminary macro design point for minimum total resistance by considering the main particulars of the catamaran vessel: block coefficient, prismatic coefficient and slenderness and separation ratios of the demihulls. Publications containing recommendations towards the optimum hull form parameters for moderate Froude numbers are reviewed and existing experimental data analysed to identify parameters for this new class of vessel. Designs with varied L/B_{OA}-ratios and constant deck area are compared to find configurations of low total resistance for carrying a nominated deadweight at a particular speed, the associated change of the light ship weight has been taken into account. Two different model test series of catamaran models have been considered and their resistance curves agreed to each other. Recommendations are made; with the most important being the vessel should not exceed a speed of Fr = 0.35, with optimal prismatic coefficients around $C_P \approx 0.5$ and low transom immersion. This study presents the preliminary design of medium-speed single and twin-hull vessels for operations close to hump speed.

NOMENCLATURE

A_{deck}	deck area (m^2)
A_T	transom area (m^2)
A_X	midship area (m^2)
B	breadth of demihull (m)
B_{OA}	breadth over all (m)
b	clearance between demihulls (m)
C_B	block coefficient (-)
C_F	ship-model correlation line (-)
C_M	midship coefficient (-)
C_P	prismatic coefficient (-)
C_R	residual resistance coefficient (-)
C_T	total resistance coefficient (-)
C_{WP}	wave pattern resistance coefficient (-)
dwt	deadweight tonnes (t)
Fr	Froude number (-)
g	gravitational constant (m/s^2)
L	vessel length (m)
m_{LS}	light ship mass (t)
P_{engine}	installed engine power (kW)
R_T	total resistance (kN)
s	separation of demihull centre lines (m)
S	wetted surface area (m^2)
T	draught (m)
U	velocity (m/s)
λ	model scale
$\eta_{transport}$	transport efficiency (-)
ρ	density (kg/m^3)
∇	volume displacement (m^3)
M	indicates model scale
S	indicates full scale
'	indicates dimensionless value

1. INTRODUCTION

High-speed catamarans have been developed during the last two decades to operate world-wide as an efficient mode of transport at sea. An important issue for researchers is the reduction of calm water resistance due to rising fuel costs and more recently emission reduction [1]. The latter reason is becoming more important due to official regulations (MARPOL 73/78, Annex VI) and society's increasing awareness of sustainability.

In the last decade, the design length and deadweight of high-speed catamarans has increased, while a maximum speed of around 40 knots has been maintained. In Figure 1 the dimensionless transport efficiency of recent Australian high-speed craft for passenger and vehicle transportation are shown. Transport efficiency ($\eta_{transport}$) is defined by deadweight tonnes (dwt), gravitational constant (g) and speed (U) over installed engine power (P_{engine}).

$$\eta_{transport} = \frac{dwt \cdot g \cdot U}{P_{engine}} \tag{1}$$

An increase in deadweight leads to an almost linear increase in transport efficiency. For vessels that operate at speeds between 32 and 46 knots and have lengths in the range of 45 to 127 m, deadweight rarely exceeds 1,000 tonnes. Two designs are noticeable, one having a very high speed of 51.5 knots, while the other has a service speed of 15.5 knots, at a comparable deadweight. While the latter one has an outstanding efficiency, the other one represents the lower boundary in terms of efficiency of the designs under consideration. Davidson *et al.* [2] presented a new catamaran design, with a length of 130 m and 1,700 deadweight tonnes with a service speed of 30 knots. Looking at the presented data, it is clear that a rise in deadweight, and a reduction in speed will achieve an increase in transport efficiency of catamaran vessels.

This study concentrates on a novel type of ship, a large medium-speed catamaran, which takes advantage of high transport efficiency gained with a significant reduction in velocity and increase in deadweight. As proposed by Davidson *et al.* [2], due to the significant design differences when compared to current high-speed craft, new guidelines on the hull form design are required. Setting speed and deadweight at a fixed deck area, a possible design can vary from a short and wide platform, utilising a beneficial viscous resistance due to reduced wetted surface area, to a slender deck structure to take advantage of narrow hulls and its favourable wave-making properties. At target velocities around hump speed, an optimum design for a minimum total resistance needs to be determined.

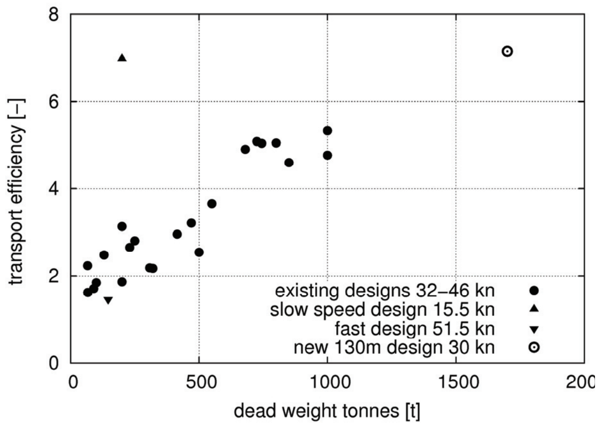

Figure 1: Transport efficiency over deadweight tonnes of recent high-speed catamarans, built in Australia [5], [4] and a lately proposed medium-speed design of 130 m in length from Davidson et al. [2].

Figure 2 displays a plot of length variation with respect to speed for displacement and high-speed ferries (monohulls, catamarans and trimarans) with data from [2], [3], [4], [5]. It shows that displacement-type vessels do not exceed a Froude numbers of 0.35, while recently developed large high speed craft have been increasing length but maintaining speed, effectively reducing Froude number to below 1.0. In addition some larger high-speed vessels (L > 100 m) have had their service speed reduced such that the Froude number approaches 0.35. It can be concluded that the new medium-speed catamaran will most likely operate in the speed regime of single-hull displacement ferries (i.e. Froude number approaching 0.35) and therefore a survey of optimum ship hull parameters will include recommendations for single and twin-hull ships. These parameters consist of Froude number, slenderness ratio, prismatic coefficient, block coefficient, demihull separation ratio and transom immersion ratio for medium-speed catamarans with a minimum total resistance.

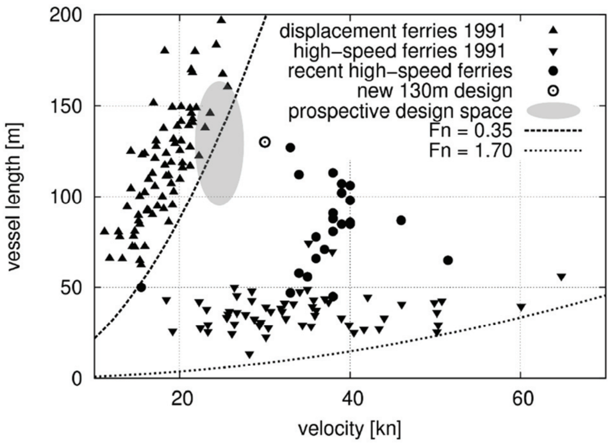

Figure 2: Selected ferries in operation displayed by length and velocity with data from [3], [4] and [5] and a proposed 130 m design [2]. Also the prospective design space for a highly efficient medium-speed catamaran is highlighted.

2. OPTIMUM HULL FORM COEFFICIENTS

As can be seen from Figure 2 the design for a highly-efficient medium-speed catamaran diverges significantly from existing modern catamaran craft. Therefore, the prospective vessel needs to be designed from a fundamental perspective. In the following sections, recommendations based on statistics from built monohull ships and model test series will be presented to find optimum hull form coefficients. Referring to Schneekluth and Bertram [6], statistical data of built ships should be questioned in determining an optimum hydrodynamic design, because it is not sure how the design was determined and changes in technology and economy may change optima over time. Nevertheless, the data presented below will provide a design starting point for the vessel type under consideration. Van Manen and van Oossanen [7] proposed that the most important design parameters for catamarans are slenderness ratio ($L/\nabla^{1/3}$), hull spacing (s/L), and wetted surface ratio ($S/\nabla^{2/3}$). These fundamental parameters form the basis of the analysis presented here.

2.1 FROUDE NUMBER

To begin a first-principles' design process, the vessel length has to be determined. For improved resistance properties, the interaction of length and velocity by the

Froude number (Fr) has to be taken into account. Michel [8] states catamarans can have a lower total resistance at around $Fr \approx 0.35$ compared to monohull designs, and fuel savings can be achieved [9]. Jensen [10] states that Froude numbers of $0.25 < Fr < 0.27$ and $0.37 < Fr < 0.50$ should be avoided, due to unfavourable wave-making and wave-breaking. A hollow in the resistance curve at around $Fr \approx 0.35$ can be seen in the majority of reviewed experimental data [2], [11], [12], [13], [14], [15], where the wave-making is approximately 60% of the ship's total resistance [6]. Beyond this velocity, a significant change in trim is related with an increased resistance gradient [2]. Therefore, a target Froude number of $Fr = 0.35$ is focused, as suggested by Davidson *et al.* [15].

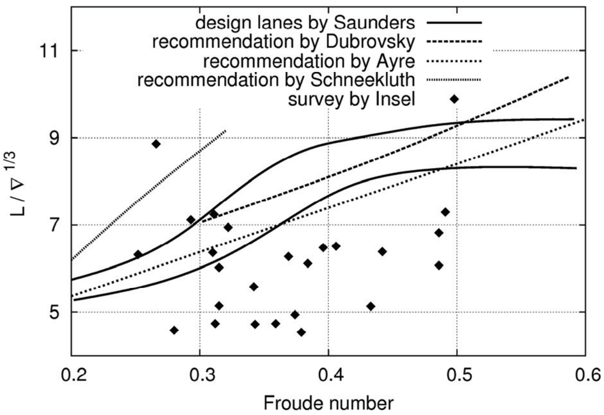

Figure 3: Recommendations for length-displacement ratio by Saunders [19], Dubrovsky [20], Ayre [6] and Schneekluth [6] and values of built catamarans by Insel [12].

2.2 SLENDERNESS RATIO

Molland *et al.* [14] state that for high-speed displacement hulls the slenderness ratio ($L/\nabla^{1/3}$) is the "predominant hull parameter" to influence calm water resistance. A slender hull is advantageous for wave-making resistance, but will increase wetted surface area and therefore frictional resistance [16]. Around hump speed the reduction of residual resistance with increasing slenderness is especially pronounced, as experimental investigations by Matsui *et al.* [17] and Molland *et al.* [14] showed. Taylor [18] investigated slenderness ratios of $5 < L/\nabla^{1/3} < 10$ in model ship series experiments, where for all considered designs a reduction in slenderness decreased residuary resistance, the closer to hump speed and the smaller the prismatic coefficient ($C_P \rightarrow 0.5$) the greater reduction of resistance could be achieved.

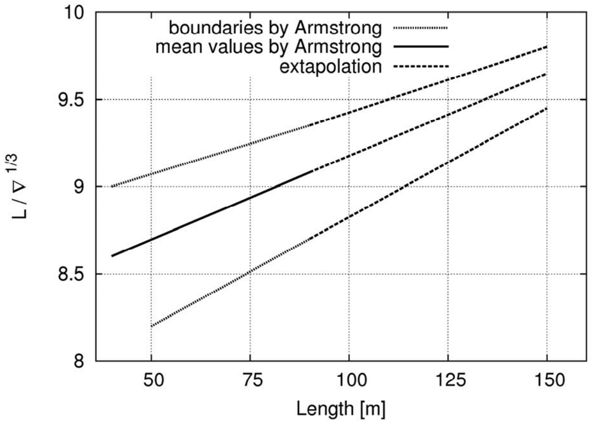

Figure 4: Slenderness ratio of existing high-speed catamarans over length by Armstrong [21].

Saunders [19] published design boundaries for length-displacement ratio variation with respect to Froude number, additionally Dubrovsky [20] and Ayre in [6] proposed recommended values. As the values by Saunders are a collection of appropriate designs of that time for merchant and combat ships, Dubrovsky proposes that his suggestions are suitable for catamarans with traditional hull shapes. In Figure 3, different propositions for slenderness can be seen. The lanes given by Saunders [19] increase for a rising Froude number and remain constant for $Fr > 0.5$, while Dubrovsky and Ayre suggest further increases in slenderness with increasing Froude number are applicable. Another approach by Schneekluth and Bertram [6] states that slenderness should be chosen for "length involving lowest production costs" for conventional ships, which surprisingly results in higher slenderness values. This approach might be questioned for medium-speed catamarans, due to significant differences in the structural design compared to conventional monohull ships. A survey from Insel [12] reports slenderness values between 4 and 8. Looking at existing high-speed craft, Armstrong [21] plotted the slenderness ratios over vessel length. In Figure 4 this observation has been extrapolated to larger ship dimensions, which are applicable for the design under consideration. The mean value, as well as the boundaries, rises linearly with the length of the vessel, while the deviation of slenderness decreases. Insel and Molland [13] reported typical slenderness ratios for high-speed displacement hulls between 6 and 9. Sato *et al.* [16] investigated catamarans utilising a slenderness ratio of 10 − 13 for an optimum performance at Fr < 1.0. Davidson *et al.* [2], [15] experimentally studied the performance of slenderness ratios of 10 - 12 for Froude numbers of $0.3 < Fr < 0.6$. Further consideration on the slenderness ratio will be made in section 3.

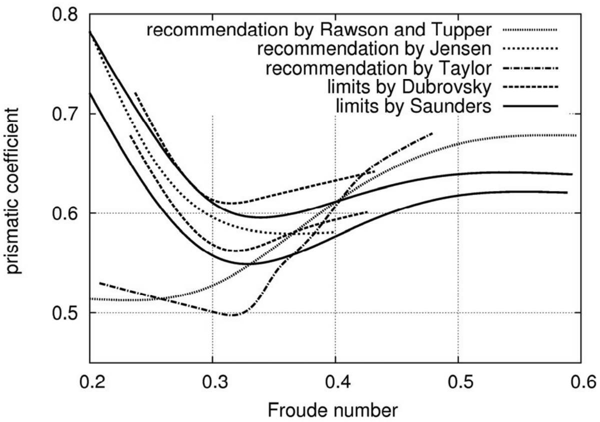

Figure 5: Design recommendations for prismatic coefficient over Froude number by different authors [22], [10], [18], [20] and [19].

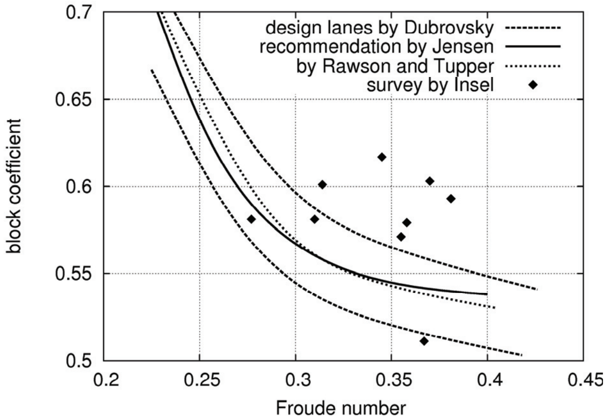

Figure 6: Recommendation for block coefficient for varying Froude number by Rawson and Tupper [22], Jensen [10] and Dubrovsky [20] and values of built catamarans from Insel [12].

2.3 PRISMATIC COEFFICIENT

The prismatic coefficient (C_P) is used to give information about the longitudinal distribution of buoyancy over the ship's length. Saunders [19] provides optimum C_P for monohull ships dependent on Froude number and Dubrovsky and Lyakhovitsky [20] for catamarans. Taylor [18] provides resistance curves from systematic model tests for varying *Fr*, C_P and slenderness ratio for different breadth-depth ratios, where C_P for lowest residuary resistance can be found. For slow speeds and hulls with low *L/B* ratio the influence of C_P on the residuary resistance is more significant, than for slender hulls at moderate speeds around $Fr = 0.5$. Jensen [10] expresses C_P over block coefficient for modern conventional ships. Considering his approach of C_B as a function of *Fr*, C_P can be plotted against Froude number as well. Rawson and Tupper [22] recommend an increasing C_P as Froude number increases. These recommendations for prismatic coefficient are summarised in Figure 5, the different estimates are matching each other, beside the latter two for $Fr < 0.35$, where smaller values are recommended.

Apart from the monotonic graphs of Jensen and Rawson and Tupper, a minimum value of C_P can be seen to be optimum at around $Fr \approx 0.32$. Vollheim [11] presented data from Guldhammer and Harvald [23], where the optimum C_P changes with respect to slenderness and Froude number, the optimum value decreases for increasing slenderness at speeds around $Fr \approx 0.35$. Beside the proposition from Dubrovsky and Lyakhovitsky [20], all recommendations made are for monohull ships. Sato *et al.* [16] state that values of C_P which are optimal for monohulls are not necessarily optimal for catamarans. They reported that buoyancy around midship (meaning a low C_P) will influence the wave-resistance positively for catamarans, this positive effect on demihull interaction has also been stated by Molland and Lee [24]. Furthermore they propose that the effect of C_P on the resistance is more significant at slow speeds, whereas a smaller prismatic coefficient is to be preferred for single and twin-hull ships using fast displacement hulls at low Froude numbers. They explain that their optimum C_P for monohulls at higher speeds being higher than Taylor's [18], since they utilised hulls having an immersed transom. As the propositions for C_P do not scatter significantly for varying Froude number, a value at the lower boundary ($C_P \approx 0.5$) may be chosen to achieve preferable resistance properties for medium-speed catamarans.

2.4 BLOCK COEFFICIENT

The block coefficient, C_B, is the ratio between the displacement and the overall main dimensions of a single hull. From experiments, Taylor [18] found a linear correlation between block coefficient and residuary resistance. Jensen [10] published a proposal for C_B for Froude numbers smaller than 0.4 for merchant ships. A similar curve has been shown by Rawson and Tupper [22], but no origin was stated. Linear approaches (block coefficient decreases linearly with increasing Froude number) such as from Alexander in [7] may be suitable for small, but not moderate Froude numbers. As can be seen in Figure 6, the optimum block coefficient decreases with increasing Froude number, but does not fall below a value of 0.5. The values surveyed by Insel [12] are in that range or even larger. However, Schneekluth and Bertram [6] say that "usual values for C_B are far greater than the value of optimum resistance." Considering this, a smaller value for resistance optimisation may be chosen. For catamarans, values by Dubrovsky and Lyakhovitsky [20] have been proposed, which align with the recommendations for merchant ships. According to Insel and Molland [13], C_B for high-speed displacement catamarans typically ranges between 0.39 – 0.45, but from experience, this coefficient is of minor importance for high-speed catamarans, because the prismatic coefficient governs the hull design.

2.5 DEMIHULL SEPARATION

The separation of demihulls can significantly influence the resistance of catamarans. This influence can be attributed to two phenomena, firstly the wave systems of the two demihulls superimpose upon each other and secondly the demihulls induce velocity fields on each other beneath the free surface [11], [25], [26]. Many studies have been done and preferable combinations of vessel velocity and demihull separation have been stated. As Eggers [27] mentions, the interference effects mainly depend on the separation-length ratio (*s/L*), rather than on clearance-width ratio (*b/B*), because the bow wave of a demihull interacts with the stern of the opposite demihull, as was mentioned by Saunders [19]. However, Dubrovsky and Lyakhovitzky [20] recommend a minimum hull clearance of $b/B > 0.75$ and Vollheim [11] even $b/B > 2.25$ to avoid undesirable cross flow effects. Everest [25] states favourable combinations are $0.2 < s/L < 0.4$ and $Fr = 0.26$ or $0.30 < Fr < 0.38$ respectively, while Froude numbers exceeding 0.38 are to be avoided. Eggers [27] found preferable powering performance experimentally at $Fr = 0.24–0.28$ and $Fr = 0.34–0.38$ for $s/L = 0.19$. Agreeing with that, Tasaki [28] mathematically found areas of reduced wave-making of twin-hulls at around $Fr \approx 0.26$ and $Fr \approx 0.34$ for varying separation ratios, as can be seen in Figure 7. With reference to his study, the optimal range of Froude numbers decreases as separation increases, with the most favourable wave interaction has been recorded at $s/L = 0.3$. As discussed in Turner and Taplin [29], wave resistance reduction can only occur due to stern waves cancelling the bow waves and an optimum interference factor is influenced not only by the separation ratio *s/L* and Froude number, but also by hull form or in particular stern shape. For catamarans with a block coefficient of $C_B \approx 0.6$ Vollheim [11] recommends $s/L > 0.3$ to minimise unfavourable effects of twin-hull induced cross flow. Typical values for *s/L* for small medium speed catamarans vary between 0.2 and 0.45 and between 1.4 and 2.4 for ratios of separation and demihull breadth (*s/B*), as reported by Insel [12].

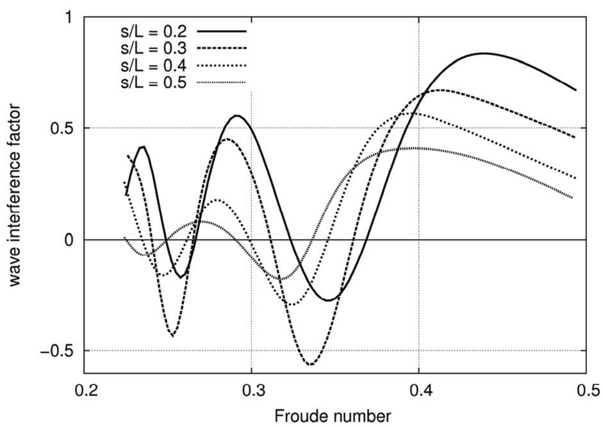

Figure 7: Wave interference factor for different separation ratios at varying Froude numbers, expressed as the difference in wave-making of a catamaran and two single demihulls in isolation, over the wave-making of the two single demihulls [28].

An experimental investigation by Insel and Molland [13] led to favourable wave interference at $0.35 < Fr < 0.42$, while they stated that viscous resistance interference is independent of speed and hull separation, but relates to *L/B* ratio of the demihulls. Molland *et al.* [14] mention that significant oscillations in the residuary resistance factor occur at low Froude numbers, where the location of favourable interference varies within the speed range as *s/L* varies. Furthermore, they state that interference decreases with increasing separation ratio and is more pronounced for catamarans having a smaller length-displacement ratios. For hulls with $L/\nabla^{1/3} = 9.5$ no favourable wave interference resulting in a reduction in wave-making could be detected.

In contrast to the above investigations, Armstrong [30] examined viscous interactions effects using double body models in a wind tunnel. A change in separation was found to influence the viscous pressure resistance rather than the frictional resistance and the maximum viscous resistance occurred at $s/L = 0.25$.

From a hydrodynamic point of view, preferable hull separation ratios can be found at $s/L \approx 0.3$, but favourable wave interaction also depends on Froude number ($Fr \approx 0.26$ and $Fr \approx 0.33$) and occurs at relatively low slenderness ratios only. Nevertheless, these combinations of demihull separation and Froude number ensure the best possible demihull interference.

2.6 RELATIVE BREADTH

In this section, recommendations for demihull breadth compared to its draught will be reviewed. For monohulls it is an important parameter to assure transverse stability [22], a criterion which does not account for catamarans due to its separated hulls. The influence of *B/T* on the drag force has been found to be small [11], [14], where an increase in *B/T* has a negative influence for resistance for low slenderness ratios, but a positive one for high slenderness ratios. Molland *et al.* [14] investigated $B/T = 1.5$, 2.0 and 2.5. Dubrovsky and Lyakovitsky [20] recommend values of 2.0 or larger and Vollheim [11] values above 1.4 for catamarans with $C_B \approx 0.6$. Insel [12] reported values of 0.8 to 2.4. A decrease of *B/T* will increase the gap between the demihulls (*b/B*) for fixed separations (*s/L*) of the demihull centre lines, if this is required. Probably most important is to choose a *B/T* ratio to ensure a minimum wetted surface area of the hull.

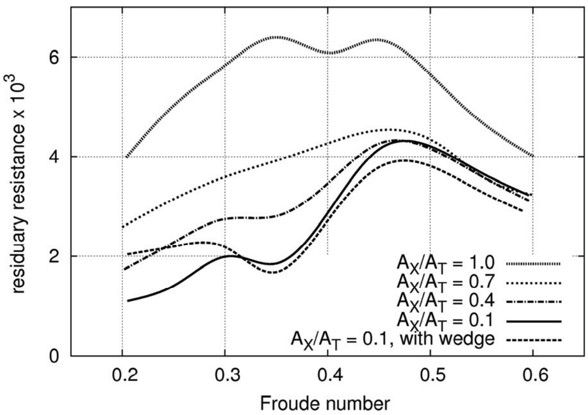

Figure 8: Residuary resistance for catamarans with s/L = 0.3 and different transom immersion ratios [14].

2.7 TRANSOM IMMERSION

Hadler *et al.* investigated different transom immersion ratios for monohulls [31] and catamarans [32] over a wide range of Froude numbers. The transom immersion ratios A_T/A_X varied from 1.0 to 0.1. Both experiments led to the conclusion that a smaller immersion reduces the residuary resistance of a ship, especially for Fr < 0.5, as can be seen in Figure 8. The same was stated by Fry and Graul [33]. A stern wedge on the hull of Hadler *et al.* [32] with A_T/A_X = 0.1 increased the relative transom area to A_T/A_X = 0.25, but delivers a further reduction in residual resistance. For catamarans, this effect is more pronounced for larger hull separations. Trim and sinkage increases for decreasing transom immersion, but this effect will be outweighed by applying the stern wedge. The hulls considered by Hadler et al. [31] have a varying C_P, which decreases with decreasing transom immersion. Therefore the resistance reduction cannot be related with the transom immersion only.

2.8 SUMMARY OF PARAMETER SURVEY

For ship hull parameters such as Froude number, prismatic coefficient and block coefficient, optimum values can be found, where the data is based on statistics from built monohull ships. Using data from different authors has led to similar conclusions regarding optimum hull form parameters, thus validating the approach. Coefficients surveyed by Insel [12] from built catamarans suggest less slender hulls which might be due to their short length (10 m < L < 40 m), which results in a relatively higher structural weight compared to larger vessels. Experiments on transom immersion showed positive resistance properties for decreasing transom immersion ratios. While combinations of Froude number and demihull separation can be found from experimental and computational investigations to achieve favourable wave interference properties, the optimum values for slenderness ratio and beam-draught ratio cannot be generally specified. To further study slenderness ratio of demihulls, the overall slenderness (L/B_{OA}) will be investigated in the next section.

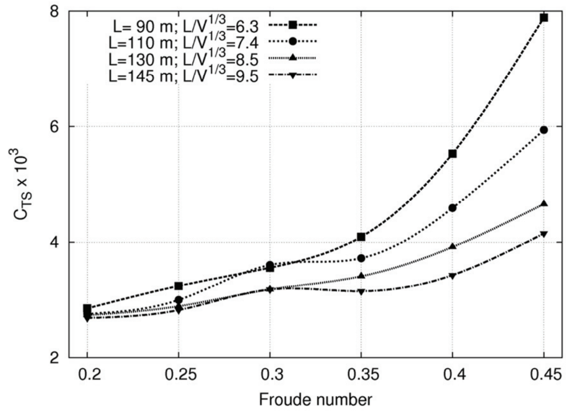

Figure 9: Total resistance coefficient for varying Froude numbers of extrapolated models of the Molland series [14].

3. OVERALL SLENDERNESS

The survey on hull parameter recommendations concluded that slender hulls have favourable wave making properties, but unfavourable wave interference properties, while hulls with a low L/B_{OA} ratio have moderate wave-making characteristics but can have favourable interference behaviour. The key question is thus: is the optimal slenderness for a single demihull in isolation the same for two demihulls in close proximity or do hull interference effects alter the value of optimum slenderness? It appears that an optimum configuration exists, which provides the lowest total resistance force at a certain speed. Therefore, experimental data of Molland *et al.* [14] and Dubrovsky and Lyakhovitsky [20] with catamaran models utilising different slenderness and separation ratios will be analysed.

3.1 MODEL TEST SERIES

The data of the model test series [14], [20] has been used to study the performance of different designs for large medium-speed catamarans carrying 4,500 deadweight tonnes on a deck area of 6,000 m^2. The deck area is assumed to be the rectangle of ship length and overall beam.

Molland *et al.* [14] undertook a comprehensive experimental series on catamaran resistance utilising different slenderness and separation ratios over a wide range of Froude numbers. Similarly, Dubrovsky and Lyakhovitsky [20] published experimental data for catamarans differing in slenderness and separation-length ratio. While the Molland series used geometrically similar NPL hulls [34] of equivalent length, the Dubrovsky series used individually designed hulls of equivalent displacement. See Table 1 for

Table 1: Fixed Parameters of the Demihulls of the Model Series under Consideration.

	L [m]	$\nabla \cdot 10^3$ [m^3]	$L/\nabla^{1/3}$	C_B	C_P	B/T	b/B
Molland	1.6	4.8-16.4	6.3-9.5	0.40	0.69	2.0	1.2-1.8
Dubrovsky	5.05-8.05	1,000	5.05-8.05	0.50-0.55	unknown	2.3-2.5	1.0

differences in the models between the authors. They both varied the separation-length ratio, while the Molland series varied s/L, whereas b/B was kept constant in the Dubrovsky series, therefore s/L varied due to a variation in demihull slenderness. This makes it possible to have designs of different slenderness with an almost constant deck area.

To study the performance of a large medium-speed catamaran, a deadweight of 4,500 tonnes and a deck area of around 6,000 m^2 has been assumed. The effect of varying light ship mass has been taken into account, it is expected that the ship's weight is proportional to the overall beam and length squared, which has been successfully validated by Davidson *et al.* [15]. Utilising the models from the model test series, appropriate full scale designs could be derived. The resulting vessels from the Molland and Dubrovsky series are shown in Table 2 and 3, respectively. Both series provide reasonably constant deck areas, where the designs using the Molland and Dubrovsky models have around 3,000 m^2 and 6,000 m^2, respectively.

3.2 EVALUATION PROCEDURE

The total resistant force (R_T) is normalised by density (ρ), velocity squared (U^2) and wetted surface area (S):

$$C_T = \frac{R_T}{0.5\rho U^2 S} \tag{2}$$

For the Molland series, the wave pattern resistance was measured, therefore the total resistance coefficient can be estimated using the form factor approach

$$C_T = (1+k)C_F + C_{WP} \tag{3}$$

with which the model-ship correlation of the total resistance can be expressed as

$$C_{TS} = (C_{TM} - C_{WP})\frac{C_{FS}}{C_{FM}} + C_{WP} \tag{4}$$

where C_{TS} and C_{TM} are the total resistance coefficients of the full scale ship and model, respectively. C_{FS}/C_{FM} is the ratio of the ship model correlation line for full and model scale. C_{WP} is the wave pattern resistance coefficient and (1+k) the form factor, both assumed to be independent of model scale.

In contrast, the resistance of the Dubrovsky series was expressed in terms of residual resistance coefficient C_R (assumed to be independent of model scale) and the full scale resistance coefficient was determined as follows:

$$C_{TS} = C_R + C_{FS} \tag{5}$$

As all the designs differ from each other in their dimensional parameters, the resistance force is non-dimensionalised by deadweight tonnes (dwt) and gravitational constant (g) to effectively compare them to each other:

$$R_T^{'} = \frac{R_T}{dwt \cdot g} \tag{6}$$

This expression includes the effect of increasing lightship weight and increasing wetted surface area for increasing slenderness, which is disadvantageous for designs with higher slenderness ratios.

3.3 RESULTS OF MODEL TEST EXTRAPOLATION

The extrapolated data are shown in two different ways of non-dimensional resistance: the total resistance coefficient (C_{TS}) and normalised resistance (R_T) for varying Froude number. Figure 9 shows the extrapolated coefficients of total resistance for different Froude numbers for the Molland model series [14]. With an exception at Fr = 0.3, the resistance coefficient decreases with increasing slenderness of the demihulls.

In Figures 10 and 11 the total normalised resistance of the different designs from both model series can be seen. All considered designs have a common resistance curve shape that shows an increasing gradient, after exceeding a certain speed, the so-called hump speed. Surprisingly, the total non-dimensional resistance does not vary significantly for the different designs below hump speed, more precisely for Fr < 0.35. This effect is

Table 2: Parameters of Considered Catamaran Designs Derived from the Molland Series.

NPL	L [m]	B_{OA} [m]	∇[m^3]	$L/\nabla^{1/3}$	s/L	A_{deck} [m^2]	S [m]	λ	C_{FS}/C_{FM}
3b	90	58	5,975	6.3	0.5	5,220	2,751	56.3	0.39
4b	110	56	6,676	7.4	0.4	6,160	3,200	68.8	0.37
5b	130	51	6,260	8.5	0.3	6,630	3,649	81.3	0.36
6b	145	40	7,270	9.5	0.2	5,800	3,825	90.6	0.36

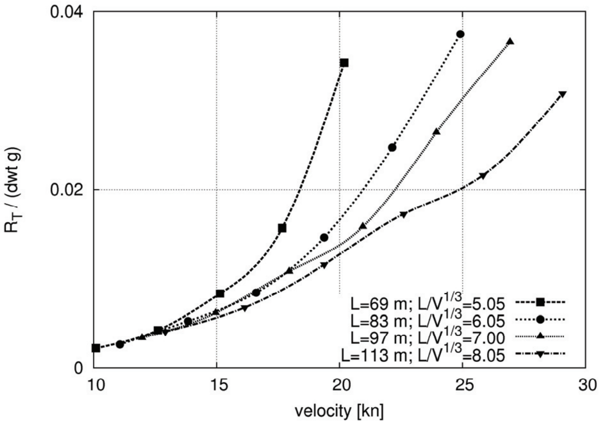

Figure 10: Normalised resistance for the extrapolated models of the Dubrovsky series [20].

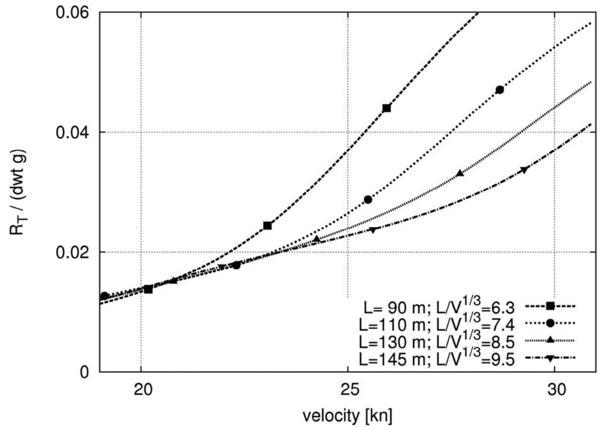

Figure 11: Normalised resistance for for varying velocity of extrapolated models of the Molland series [14].

especially distinctive in the Molland series, whereas Dubrovsky's models have smaller slenderness ratios, this dramatic increase in normalised resistance with decreasing slenderness occurs at lower velocities, compared to Molland's models. The design with the highest slenderness ratio in the Dubrovsky series shows a slightly lower resistance over a wide speed range. This might be physical or due to the better design of the slender hull. Furthermore, the authors are aware that the speed-wise resolution of ΔFr = 0.05 is relatively coarse for such investigations, data points have been interpolated using C-spline interpolation.

To study the influence of the demihulls on each other, resistance over slenderness is plotted for a catamaran and a single demihull in isolation in Figure 12, where values of single demihulls have been normalised by half deadweight, respectively. If the different designs operate at 30 knots, a significant reduction of resistance can be achieved with an increase in slenderness. At 25 knots, the decrease in resistance is less pronounced and the difference for the two catamarans with the slenderest hulls is small. At 20 knots, no significant differences in resistance can be observed for changing slenderness ratios of the catamaran, while the resistance of the demihull in isolation decreases with increasing slenderness. For a slenderness of $L/\nabla^{1/3}$ = 6.3 the normalised resistance of a catamaran is almost equal to that of the single demihull, while for all other cases a negative demihull interaction is reported.

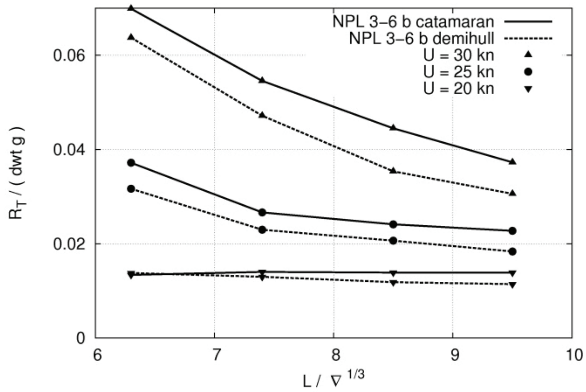

Figure 12: Normalised resistance for catamaran and single demihulls in isolation at different slenderness ratios at certain velocities

3.4 VALIDITY OF MODEL TEST RESULTS

The results of the extrapolation have to be interpreted carefully. While the Molland models are relatively small which results in large scale factors (56 < λ < 90), details on the geometry of the Dubrovsky models are not known. Furthermore, the prismatic coefficient of the NPL hulls is considerably higher (C_P = 0.69) than the recommended values of $C_P \approx 0.5$, which could further improve the resistance properties, but also change the outcome of this study. The fluctuation of deck area between the different designs of the Molland series may further diffuse the results, because a correction of the hull separation to achieve the correct deck area will influence the displacement due to a change in light ship weight and the resistance due to a change in demihull interference. It must be mentioned that these results are valid for NPL-like hull forms with a relatively large water surface area and sections with high deadrise angles and round bilges throughout the ship length [34]. The results may differ for other kinds of hulls forms, such as wave piercer hulls, which have a fine bow fairing into fuller round bilge midship

Table 3: Parameters of Considered Catamaran Designs Derived from the Dubrovsky Series.

model	L [m]	B_{OA} [m]	∇[m^3]	$L/\nabla^{1/3}$	s/L	A_{deck} [m^2]	S [m]	λ	C_{FS}/C_{FM}
2	69	41.1	5,040	5.05	0.40	2,835	2,271	13.7	0.56
3	83	35.6	5,220	6.05	0.29	2,955	2,402	13.7	0.57
4	97	30.6	5,360	7.00	0.21	2,970	3,091	13.9	0.57
5	113	27.1	5,550	8.05	0.16	3,060	3,528	14.0	0.57

sections, while the aft quarter of the hull is described by hard chine sections with a deep square transom [2]. A larger optimum slenderness for wave-piercer hull forms may be expected due to a relatively smaller wetted surface area.

4. DESIGN CASE

The extrapolation of the model test results leads to the starting point of a favourable design of a medium-speed catamaran carrying a deadweight of 4,500 dwt on a deck area of 6,000 m^2. Considering a desired service speed of 22.5 knots, from Figure 11 it can be concluded that a minimum resistance is able to be achieved across three different configurations of 110 m, 130 m and 145 m. Given minimum building cost for the shortest vessel, 110 m can be considered being the optimum length. With a slenderness ratio of $L/V^{1/3} = 7.4$ and $s/L = 0.4$, the ship will then operate at $Fr = 0.35$. Satisfyingly, this Froude number provides reduced wave-making and desirable wave interference. In contrast, at Froude numbers of 0.26 favourable wave interference can also be achieved [28], but wave-making properties are poor [10]. The slenderness ratio resulting from the model test extrapolation correlates with the recommendations for slenderness in Figure 3, where a slenderness in the range from $7 < L/V^{1/3} < 8$ is considered optimal. From Figure 5 it can be seen that a prismatic coefficient of around $C_P = 0.55$ and from Figure 6 that a block coefficient of $C_B = 0.5$ would be ideal. It has to be kept in mind that catamarans perform better at lower prismatic coefficients compared to mono-hulls [16] and furthermore that the average values of the block coefficient are larger than those for optimum resistance [6], thus values of $C_P = 0.5$ and $C_B = 0.4$ are chosen.

Considering 26 knots as a proposed service speed, the length providing the least resistance over deadweight would be 145 m with a slenderness ratio of $L/V^{1/3} = 9.5$ regarding to Figure 11. Again, the combination of length and speed results in a Froude number of $Fr = 0.35$. This means, that the optimum slenderness of a demihull cannot be determined by the Froude number only, also the length scale and velocity must be taken into consideration, which may be due to the changing ratio between normal and tangential stresses on the hull. Both, Froude number and Reynolds number need to be considered.

Figure 13 shows a possible demihull design of a large medium-speed wave-piercing catamaran with a deck area of 6,000 m^2, carrying 4,500 dwt at a speed of 22.5 knots. The form is characteristic for a wave-piercer hull form, having a fine bow evolving into semi-circular midship sections, while the aft of the hull is described by hard chine sections with a rectangular transom and a stern wedge. Ideally the transom immersion is zero, but practically larger due to the stern wedge. The hull has a slenderness ratio of $L/V^{1/3} = 7.4$, a prismatic coefficient of C_P=0.5, a block coefficient of $C_B = 0.4$ The hull form coefficients are summarised in Table 4. The draft of 6.1 m is significantly larger compared to 3.9 m of the INCAT 112m hull [5].

Referring to Figure 1, the design under consideration carrying 4,500 deadweight tonnes at 22.5 knots will be able to reach a transport efficiency of

$$\eta_{transport} \approx 26$$

which is more than three times the efficiency of any recently built catamaran ferries for vehicles and passengers. It also proves the almost linear rise of transport efficiency with increasing deadweight. To estimate this, an overall propulsive efficiency of 0.5 and extrapolated resistance values from the NPL model test series have been considered.

Furthermore, the parameters were determined for minimum resistance force of medium-speed catamarans, but aspects such as production costs, seakeeping properties, port conditions, compatibility with the propulsion system and aesthetics may have to be considered for future catamarans.

Table 4: Hull Form Parameters for a Large Medium-Speed Catamaran carrying a deadweight of 4,500 dwt, on a Deck Area of 6,000 m^2 at 22.5 knots.

Fr	$L/\nabla^{1/3}$	C_P	C_B	s/L	L/B_{OA}	B/T
0.35	7.4	0.51	0.39	0.40	2.0	2.0

5. CONCLUSIONS

This article comprised recommendations of the most important hull parameters influencing the macro hydrodynamic design for lowest resistance for medium-speed catamarans. Initial design values for Froude number ($Fr \approx 0.35$), prismatic coefficient ($C_P \approx 0.5$), and block coefficient ($C_B \approx 0.4$) can be found from recommendations based on statistics of built monohull ships. Experiments suggest that reducing the transom immersion ratio reduces resistance for monohulls and

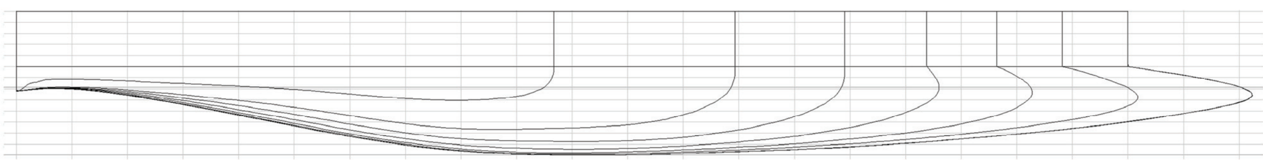

Figure 13: Profile and buttocks of a possible design for a demihull of medium-speed wave piercing catamaran with a length of L = 110 m and a draft of T = 6.1 m.

catamarans at the speed range under consideration, but also the associated decrease of the prismatic coefficient contributes towards this outcome. Values for slenderness and separation ratio can be found due to the analysis of existing model test data using NPL hull forms, where a slenderness ratio *of* $L/\nabla^{1/3} = 9.5$ and a separation ratio of $s/L = 0.2$ provide the best resistance properties for the designs specified. If the different designs do not exceed a Froude number of 0.35, the resistance compared to their deadweight does not vary significantly at a certain speed. For a medium-speed catamaran with a service speed of 22.5 knots, a nominated deadweight of 4,500 tonnes and a deck area of 6,000 m^2, the design with the lowest resistance would have a length of 110 m and an overall breadth of 56 m. A transport efficiency more than three times higher than that of state-of-the-art catamaran ferries can be achieved. The value of demihull separation influences various aspects of the ship concept, such as design (deck area), structure (light ship weight) and hydrodynamics (wave interference). Furthermore, it can be stated that both demihulls need to be considered for optimisation purposes. Froude numbers of 0.35 do not only provide favourable wave-making, but also desirable wave interference properties. Ultimately, the total resistance of the full-scale catamaran has to be minimised, but further criteria such as seakeeping, propulsion systems and production issues need to be considered.

In future studies, the derived preliminary design will be used as an initial design for further optimisation towards a minimum drag force using numerical CFD (computational fluid dynamics) tools. They will allow the evaluation of a more comprehensive design matrix toward a minimum resistance for highly efficient medium-speed catamarans.

6. ACKNOWLEDGEMENTS

This research has been conducted as part of a collaboration research project between Incat Tasmania Pty Ltd, Revolution Design Pty Ltd, Wärtsila, MARIN and the Australian Maritime College at the University of Tasmania. It was supported under Australian Research Council's Linkage Projects funding scheme (project number LP110100080).

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