INCREASING PERFORMANCE USING HYBRID CATAMARAN HULL DESIGNS

BY

Dr. Robert Latorre
Naval Architecture and Marine Engineering
911 Engineering Building
University of New Orleans
New Orleans, LA. 70148
Tel (504)-280-7180
Email rglnae.uno.edu

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ABSTRACT

There is a growing interest world wide in catamaran vessels. The catamaran's large deck area and high transverse stability make it attractive for recreational and commercial craft. To improve the catamaran resistance and powering, a number of researchers have tested the catamaran with hydrofoil. This paper reviews their research and shows that fitting the hydrofoil to the catamaran hull can result in a 25% decrease in resistance or 8% increase in speed, as well as improved sea keeping.

1. INTRODUCTION

There is a growing interest worldwide in catamaran vessels. The catamaran's large deck area and high stability make it an attractive for recreational and commercial craft. For these features the catamaran operator is willing to accept some increase in catamaran hull frictional and wave resistance. To reduce the catamaran resistance, it is possible to use a hybrid catamaran craft, which utilizes planning surfaces, hydrofoil and / or air cushion to reduce resistance.

These can be understood from Table 1. This table summarizes several hybrid catamaran designs, which are currently being developed. The hydrofoil catamaran (Hybrid II) has been under development for the past two decades. Aframeev (1978) completed a series of model tests with different foil locations. Calkins (1985) presented the results of a 100 ton 300 passenger 32m HYCAT. Miyata (1989) reported the hydrodynamic development of a 200 ton 40 knot passenger hydrofoil craft. Both Calkins and Miyata adopted a design with 80% hydrofoil support and 20% planning/displacement support at design speed. Zhao (1997) presented the results from systematic tests over a number of hull loadings and LCG positions. The main particulars of these hydrofoil catamarans are summarized in Table 2. These test results have remained unconnected. This paper is an attempt to unify these results for high-speed recreational and commercial craft design.

2. NOMENCLATURE

a = acceleration
B = ship beam
B'= hull separation ratio
b = demi-hull beam
b_s = catamaran hull separation

C = chord length of hydrofoil
C_L = lift coefficient
C_T = total resistance coefficient
C_Δ = Loading coefficient
F_n = Froude number based on water line length of ship
F_∇= Froude number based on cube root of displacement volume
g = gravitational acceleration
HP = Engine horsepower
K = Wave number
K= speed coefficient
L= length of ship
Q= power coefficient
R_T = total resistance
T = draft
t = maximum hydrofoil thickness
X_a = aft foil location from transom
X_c = center foil location from transom
X_f= forward foil location from transom
X_g = center of gravity location from transom
V = speed
V_k = speed in knots
z = heave amplitude
α = angle of hydrofoil incidence
β = resistance reduction ratio
ε = Resistance ratio R_T/Δ
ζ_a = wave amplitude (1/2 wave height)
θ = pitch amplitude
φ = trim angle
λ_e = encounter wave length
ρ = density of water
∇ = displacement volume
Δ = displacement

3. HYDROFOIL CATAMARAN ADVANTAGES

The advantage of the hydrofoil catamaran can be understood from the improvements of catamaran and the hydrofoil craft. The addition of hydrofoils increases the catamaran's structural strength. The hydrofoils also reduce the catamaran resistance. Without hydrofoils, there is a significant wave formation between the catamaran hulls. These waves result in higher resistance as the speed increases. This is shown schematically in Fig.1 from Aframeev (1978).

At small speeds $V = V_1$, a series of waves form (Fig.1-a).
At moderate speeds $V=V_2$ the first wave increases into a long wave with a trough located near the middle of the boat.(Fig. 1-b)

At high speeds $V=V_3$ the wave shifts back and forms a crest near the stern. (Fig. 1-c).

At maximum speed $V=V_4$, the wave crest forms at the stern (Fig. 1-d). This results in larger wetted surface inside the tunnel and an increase in catamaran resistance.

At higher speeds, this stern wave breaks with further increase in resistance.

It is possible to use the foils to cancel the waves formed between the catamaran hulls. There is always a depression in the free surface formed behind a shallow submerged hydrofoil. By proper placement of the hydrofoils they can cancel the waves between the catamaran hulls (similar to a bulbous bow). This results in a lower free surface without waves as shown in Fig 1-d.

By proper selection of the hydrofoil number and position it is possible to reduce the water level, decrease wave resistance and wetted surface. This was used to determine the forward, center, and aft foil positions, Xa, Xc, and Xf, in Table 2. At high speeds there is also spray drag. Several authors have used spray strips to reduce the foil-generated spray.

As the hydrofoil craft reaches the design speed, the hydrofoils generate lift and the hull draft is reduced. In some hydrofoil catamarans, the foil support is in the range of 25-40%.

With high-speed hydrofoil catamarans, the foil lift is 60%-80% of the boat weight. These hydrofoil catamarans are similar in operation to hydrofoil craft. The submerged catamaran hulls acts as end plate and effectively increase hydrofoil aspect ratio by reducing it's induced drag. The side hull provides a certain amount of dynamic stability in heave, pitch and roll. This results in smaller catamaran motion in waves. The rough water performance for these high-speed hydrofoil catamarans without active foil control is between a surface piercing hydrofoil and a fully submerged hydrofoil. There have been several reports of "wave crashes" in waves. The hydrofoil angle of attack changes due to the orbital motion of seaway and its lift decreases causing a "crash" Payne (1997). So when foil lift is large, it is useful to consider a dynamic foil control.

Several high-speed hydrofoil catamarans with active foil control are summarized in Table 3. These include the Japanese built Superjet 30 and the SSTH 30 (Phillips 1994). Their good performance can be judged by the plot of power coefficient Ⓠ versus speed coefficient Ⓚ in Fig 3.

Power coefficient

$$Ⓠ = 0.148 \text{ B.H.P}/ \Delta V_S \qquad (1)$$

Speed coefficient

$$Ⓚ = 0.583 V_S / \Delta^{1/6} \qquad (2)$$

These values of hydrofoil catamaran power coefficient are below the 1970 performance line, which indicates their superior performance as high-speed marine vehicles.

4. HYDROFOIL CATAMARAN RESISTANCE

The body plan of model 3W tested by Zhao et. al. (1997) as shown in Fig 3. The arrangement of hydrofoils and aft flap is shown in Figure 4a. The influence of the hydrofoil on the catamaran hull resistance is shown in Fig 5. Here the results are presented in non-dimensional form.

Displacement Froude number F_∇:

$$F_\nabla = V/ \sqrt{g}\nabla^{1/3} \qquad (3)$$

Resistance displacement ratio $\in$:

$$\in = R/ \Delta \qquad (4)$$

Hull loading coefficient C_Δ:

$$C_\Delta = \Delta/ \rho\, g(2\, b)^3 \qquad (5)$$

In Figure 5, the dashed lines are for the catamaran 3W without hydrofoils and the solid lines are for the hydrofoil catamaran. The hydrofoils had a simple cross section at a flat bottom and circular top. The resistance coefficient can be characterized the influence factor β given by :

$$\beta = \in_h / \in_o \qquad (6)$$

Where:

$\in_o$ = with out hydrofoil
$\in_h$ = with hydrofoil

The values of β are in the range of $0.6 < \beta < 0.75$ depending on the load coefficient and Froude number. Details of the loading coefficient are in Table 4. The foils are designed to carry about 40 – 60% of the boat weight depending on the boat speed. These tests show that fitting the hydrofoils can reduce the catamaran resistance by 25% which results in a 8% speed increase.

Aframeev (1978) tested a mono hull planning craft shown in Fig 6. It was then separated along its center to obtain a catamaran hull. In order to compare the resistance coefficients, the hull loading coefficient C_Δ was kept constant at $C_\Delta = 0.6$. The results of the planning hull and the catamaran fitted with different hydrofoil arrangement are shown in Fig 7. In these tests the non-dimensional separation distance B' was kept constant.

$$B' = b_s/ 2b = 0.75 \qquad (7)$$

The hydrofoils have a simple cross section with a flat bottom and circular top. The chord is 15cm with a thickness to chord ratio of 0.06.

The resistance curves in Figure 7 indicate several interesting features of the hydrofoil catamaran wave interaction. For $F_\nabla < 1.5$, the values of $\in$ are close. At $F_\nabla > 1.5$, the influence of the waves formed inside the catamaran without hydrofoils (curve a) increase the catamaran resistance over the mono-hull values (curve h).

This increase is unchanged when the hydrofoil is fitted near the bow (curve g). The forward foil has little influence since the majority of the resistance increase occurs at stern where the wave crest forms. This accounts for why the catamarans with stern foils (curves b and e) have low resistance $\beta = 0.65$. At $F_\nabla = 2.7$ the hydrofoil catamaran with three foils (curve b) has the lowest resistance $0.6 < \beta < 0.7$over the entire speed range. This illustrates the effect of the wave cancellation by the hydrofoil. This wave cancellation is also clear from the constant trim angle of the hydrofoil catamaran with three foils (curve b) above $F_\nabla > 1.5$.

Miyata (1985) tested hydrofoil catamarans HC200A and HC200B fitted with three hydrofoils. The hydrofoils have a simple cross section with a flat bottom and circular top. The chord is 25.9cm with a thickness of 0.0106. These craft have more than 80% of the hull weight supported by the hydrofoil lift. The body plan the catamaran hulls are shown in Fig 8. By arranging the three hydrofoils it is possible to achieve wave cancellation and reduce the catamaran resistance. The model test results in Figure 9 show the resistance is reduced to 40% by fitting the catamaran with hydrofoils at the design speed $F_\nabla = 2.7$.

5.HYDRFOIL CATAMARAN SEAKEEPING

The most complete published set of hydrofoil catamaran sea keeping tests are those performed by Calkins (1985) and Miyata (1989). They performed tests with the hydrofoil catamaran models advancing into head seas. In Miyata's tests with model HC 200B, waves with $H_w/L = 0.0336$ and $\lambda / L = 1.05\text{-}3.68$ were used. For the HC200B, a 38.08m, 200 ton hydrofoil catamaran these waves have a 1.28m height and 40-140 m lengths.

Calkins (1985) tested the 0.61m hydrofoil catamaran shown in Figure 10 in calm water and head seas. The tests were made using non-dimensional wave height of H_w / L of 0.40 and 0.066 and wave lengths λ / L of 1, 2, 3, 4, 5 and 6.
The test results of Calkins and Miyata are shown for the pitch transfer function (PTF) in Figure 11.

$$PTF = \theta / K\zeta_a \qquad (8)$$

Fig 12 shows the heave transformation function (HTF)

$$HTF = Z / \zeta_a \qquad (9)$$

The reason for the different values of PTF and HTF between the Hycat and the HC200B is due to the difference in catamaran hull forms. The sharper and deeper twin hull configuration of HC200B has better sea keeping properties. The HYCAT has relatively small under deck clearance and a larger hull change with depth. These results indicate two important points:

I. To minimize the catamaran hull influence on the pitch and heave motion in waves it is necessary to utilize slender hulls with small cross section as well as a large clearance between the cross structure and water surface.

II. To avoid the influence of the wave orbital motion it is useful to increase the depth of hydrofoil submergence. Otherwise the pitch and heave motion are primarily due to the fluctuation in the hydrofoil lift due to the proximity to the free surface.

The hydrofoil arrangement for model HC200B-AZ are shown by schematically in Fig 13. The hydrofoil catamaran ride comfort is determined by its vertical acceleration at mid ships or LCG. These are compared in Fig 14. The PT150 is a surface piercing hydrofoil boat while the jetfoil is a submerged hydrofoil craft with motion control using dynamic control of the hydrofoil. Figure 14 shows the two hydrofoil catamarans, the HYCAT and the HC200B, have acceleration values that fall between the PT 150 and the jetfoil hydrofoil craft.

CONCLUDING REMARKS

This paper has presented the results of a three lectures on the resistance and sea keeping of the hydrofoil catamaran. The results of the resistance and sea keeping tests here been compared in this paper. They support the following conclusions.

1. At high speeds, $F_\nabla > 1.5$ waves form between the catamaran hull creating increased resistance.
2. By proper placement of the hydrofoil between the hulls it becomes possible to reduce the wave height and reduce the catamaran resistance by 25-50% deeply on the amount of the hull weight supported by hydrofoil lift.
3. Properly arranged hydrofoils will then reduce the wave height, the wetted surface and the catamaran resistance resulting in a speed increase of 8-10%.
4. Comparison sea keeping tests have shown the importance of using a slender catamaran hull with large clearance between the water and hull cross section to minimize the heave and pitch motions.
5. Increasing hydrofoil depth of submergence results in reduced hydrofoil catamaran response by minimizing the influence of the free surface fluctuation on the hydrofoil lift.

The design data presented here is useful for designing a high-speed recreational or commercial hydrofoil catamaran.

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Displacement Catamaran	Planning catamaran	Hydrofoil Catamaran	Surface effect Ship (SES)

Table 1 Summary of hybrid Catamaran Designs

			Aframeev (1978)	Calkins (1985)	Miyata (1989) HC200A	Miyata (1989) HC200B	Zhao (1997) 3 W
Length	L	M	2.71	0.61	1.6	1.19	2.61
Beam(Overall)	B	M	1.06	0.24	0.4	0.362	0.884
Demi-Hull Beam	b	M	0.30	0.13	0.096	0.1071	0.324
Draft	T	M	N.A	0.02	0.17	0.206	variable
Displacement	Δ	Kg	130.6	2.07	6.185	6.185	54.4
Center of gravity location	LCG/L	_	0.43	0.34	0.375	0.378	0.323
Forward foil location	L_f / L	_	Variable	0.71	0.692	0.672	0.5
Center foil location	L_c / L	_	_	_	0.332	_	_
Aft foil location	L_a / L	_	Variable	0.18	0.102	0.084	0.2
Load coefficient	C_Δ	_	0.6	0.109	0.873	0.629	0.2

Table 2. Main Particulars of catamaran with foils. 1978 to present.

	HYCAT	CATAFOIL	SUPER JET-30	SSTH 30
Length	80.68	118.08	103.22	99.71
Beam	29.84	32.8	32.14	18.36
Draft	2.95	3.28	9.184	6.56
Δ	101.346	110	190	94.3
Speed	35.1	45	40	28.2
Passenger	302	350	200	68
S.H.P	4289.5	5187.6	9997.2	1179.6
T.E (Transport efficiency)	5.35	6.56	5.2	15.5
$V/\sqrt{g}\,\nabla^{1/3}$	2.8	3.6	2.95	1.52
$K = 0.583\ V_S/\Delta^{1/6}$	9.47	11.9	9.72	7.70
$Q = 0.148$ B.H.P/ $\Delta\ V_S$	0.178	0.155	0.19	0.06

Table 3. Particulars of hydrofoil catamaran.

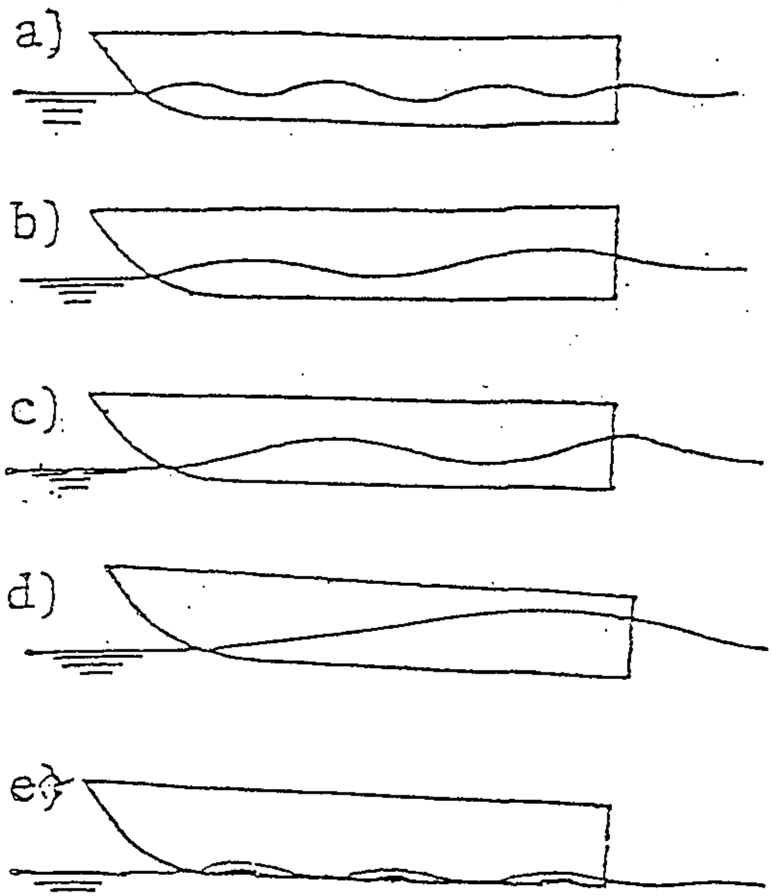

Figure 1. Observed profile between Catamaran hulls (Aframeev 1978)
A) low speed V_1
B) Speed $V_2 > V_1$
C) Speed $V_3 > V_2$
D) Maximum speed V_4
E) Speed V_4 with three hydrofoils

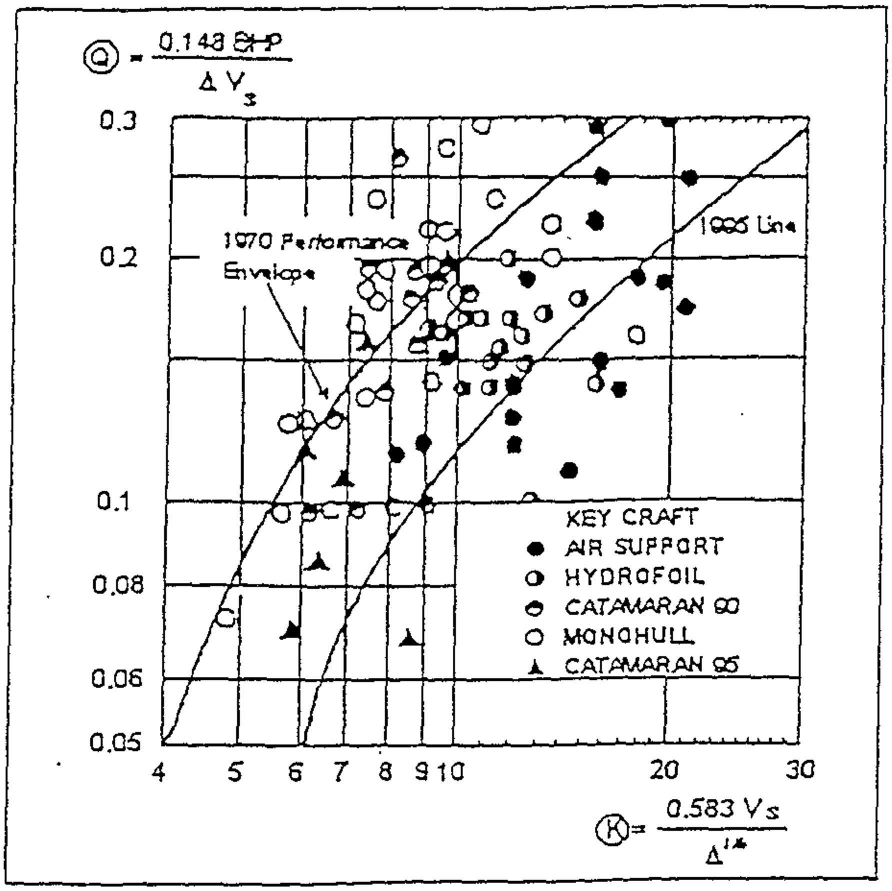

Fig 2. Comparison of Hydrofoil Catamaran performance with other High-speed craft

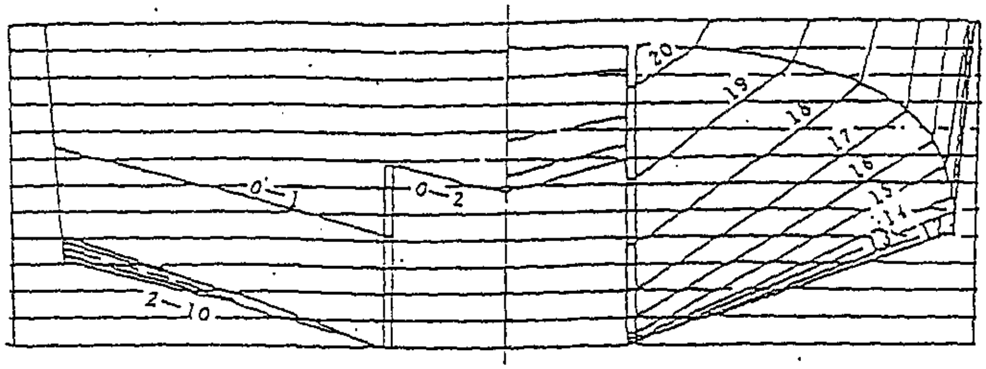

Fig 3. Body Plan of Hull 3W tested by Zhao(1997) details in Table 2.

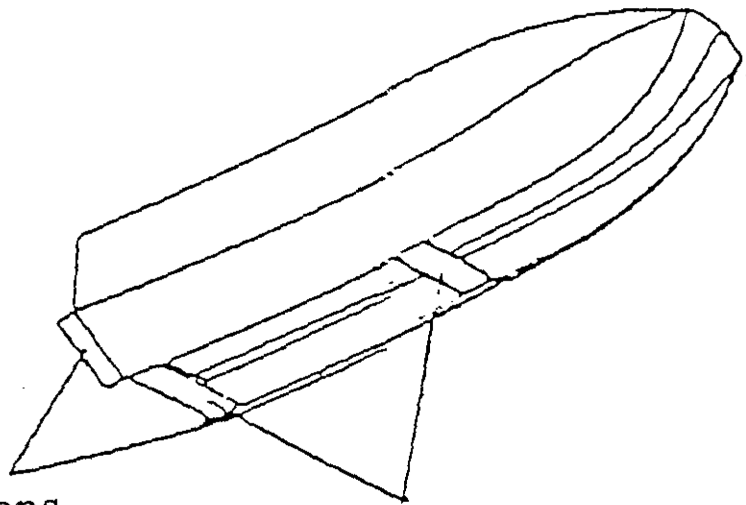

Fig 4. Arrangement of Hydrofoils and aft flaps (Zhao 1997).

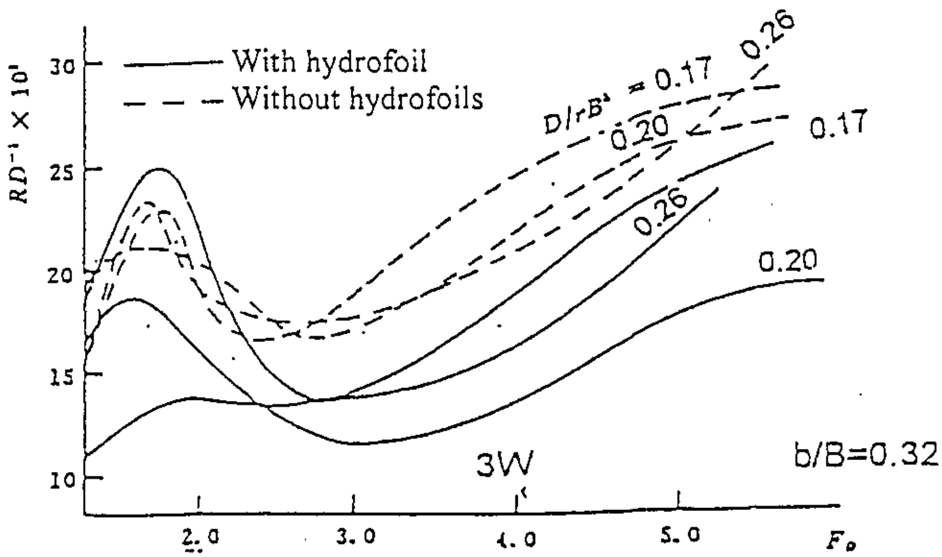

Fig 5. Comparison of catamaran model 3W resistance coefficient ε with and with out hydrofoil for different loading coefficients C_{Δ} (Zhao 1997)

Key

——— With hydrofoil

– – – Without hydrofoils

1- $C_{\Delta} = 0.17$

2- $C_{\Delta} = 0.20$

3- $C_{\Delta} = 0.26$

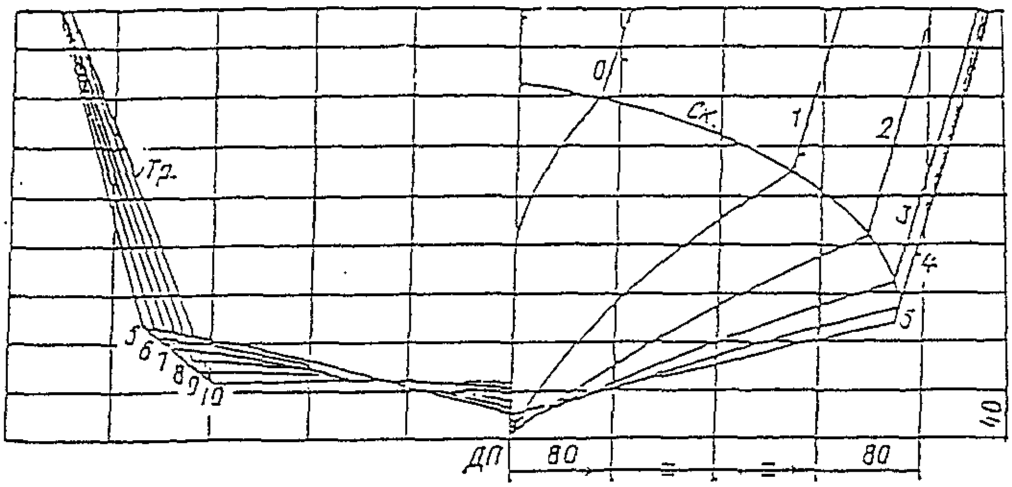

Fig 6. Body plan of hydrofoil catamaran tested by Aframeev (1978) shown here as mono-hull without hull separation.

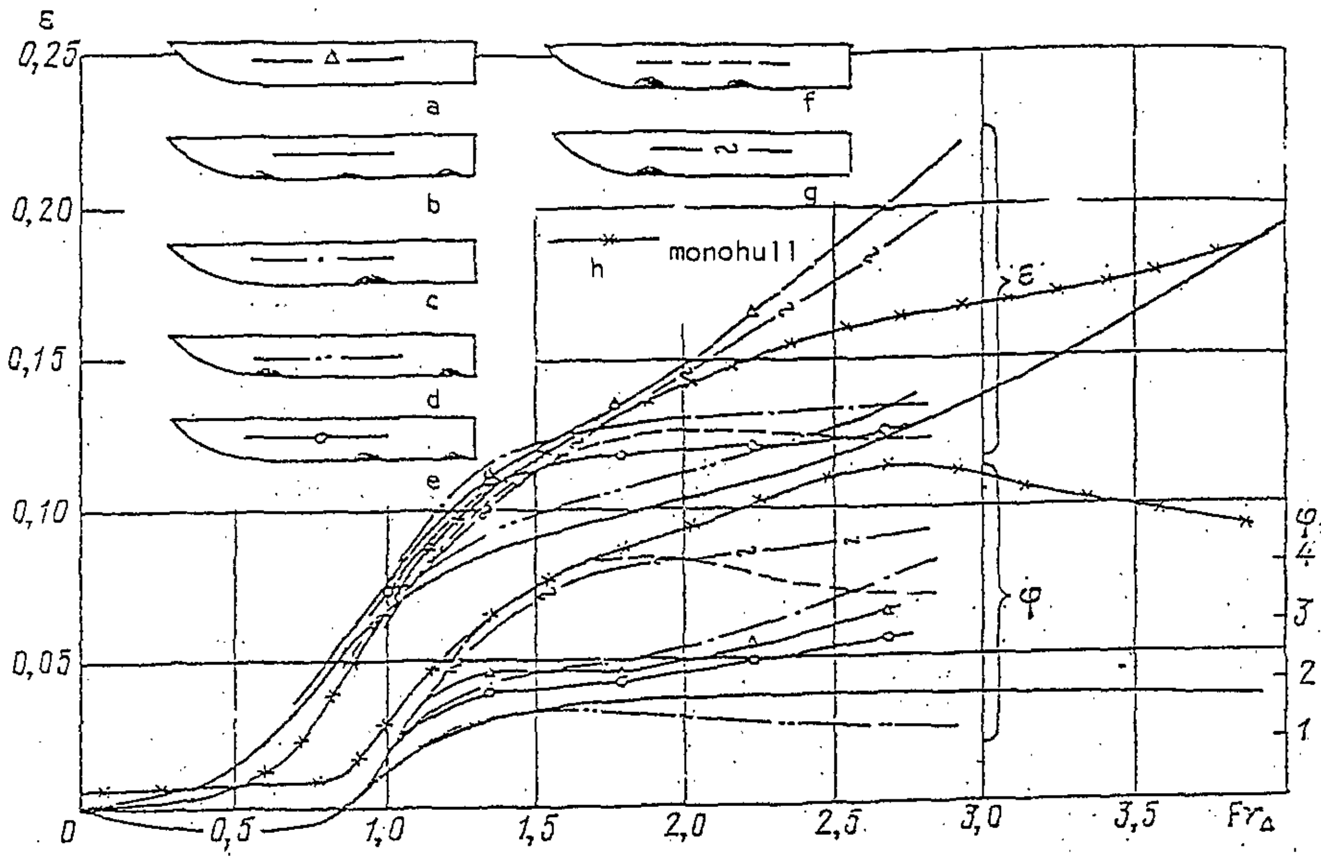

Fig 7. Comparison of monohull and catamaran resistance coefficient ε and trim angle with various hydrofoil locations. $C_\Delta = 0.6$, $X_g=0.43$, $\alpha=0$ (Aframeev 1978).

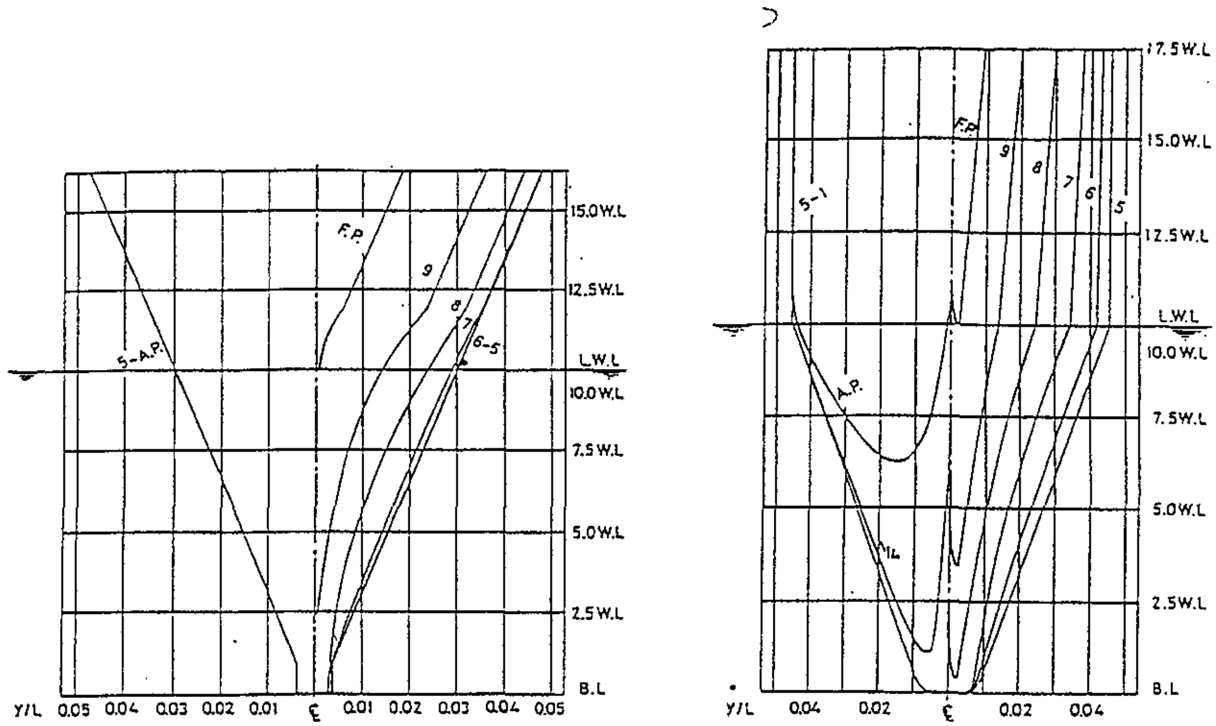

Fig 8. Body plan of hydrofoil catamarans tested by Miyata (1989)

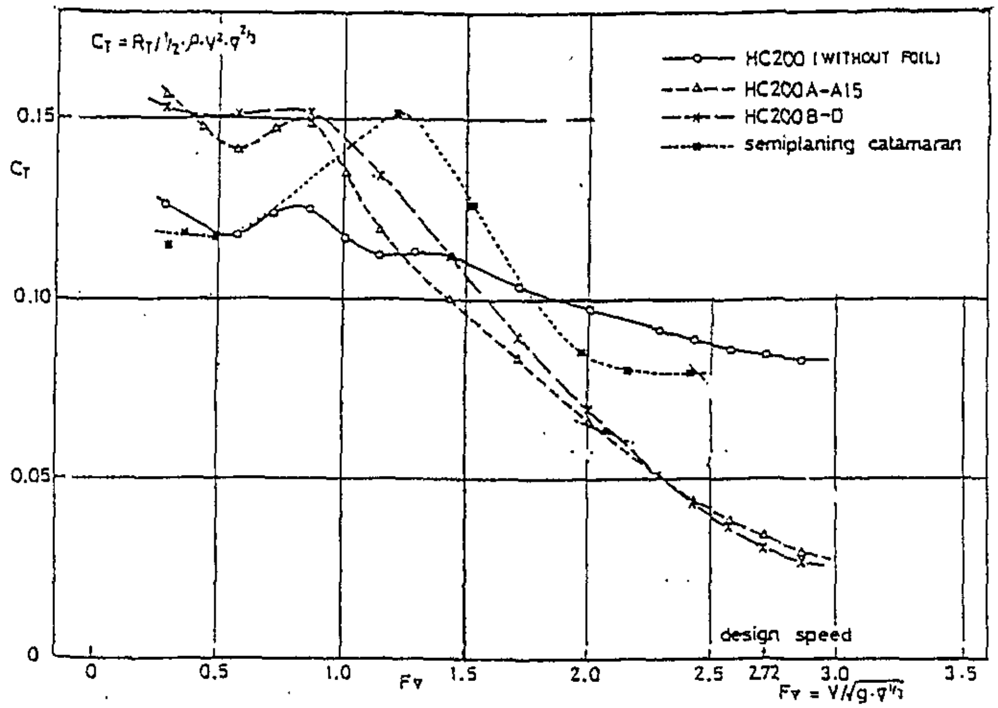

Fig 9. Comparison of hydrofoil catamaran resistance coefficient C_T with and without hydrofoil (Miyata 1989).

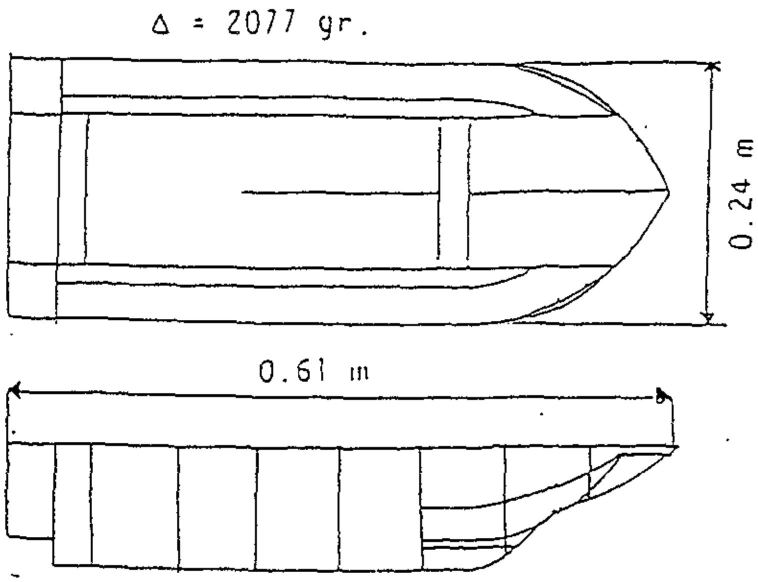

Fig 10. Hydrofoil catamaran HYCAT tested by Calkins (1985)

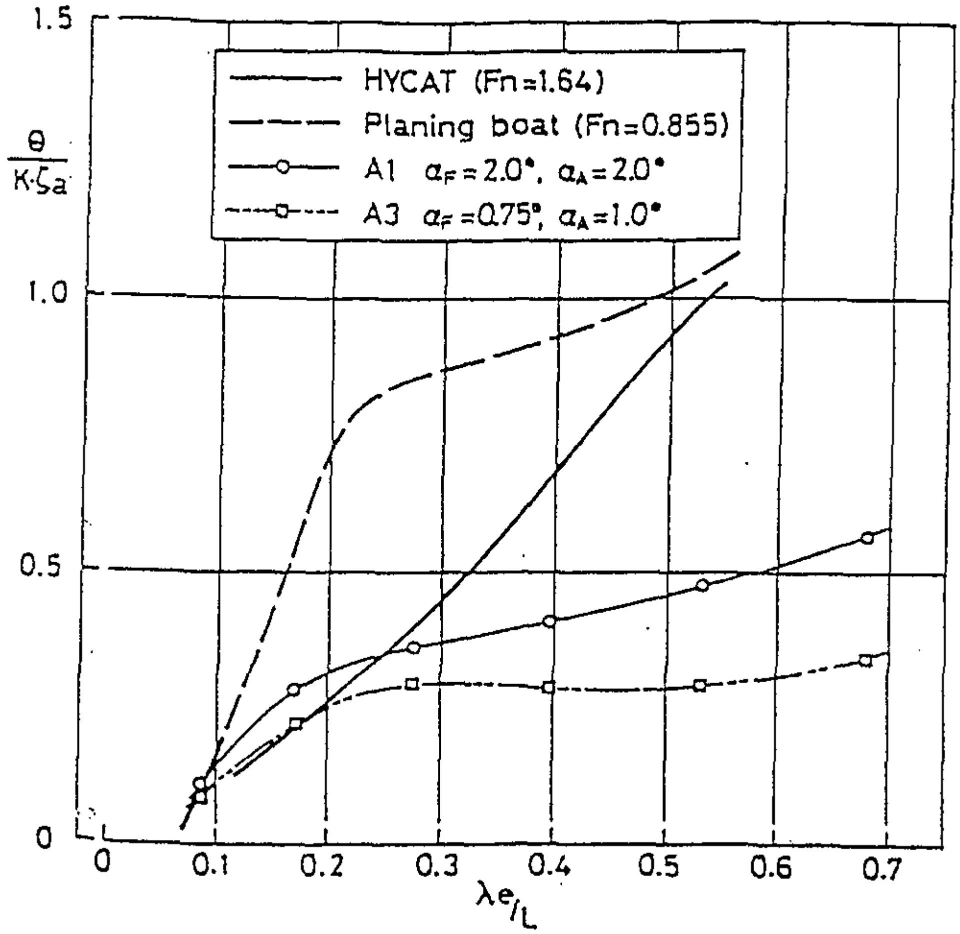

Fig 11. Comparison pitch transfer function (Miyata1989)

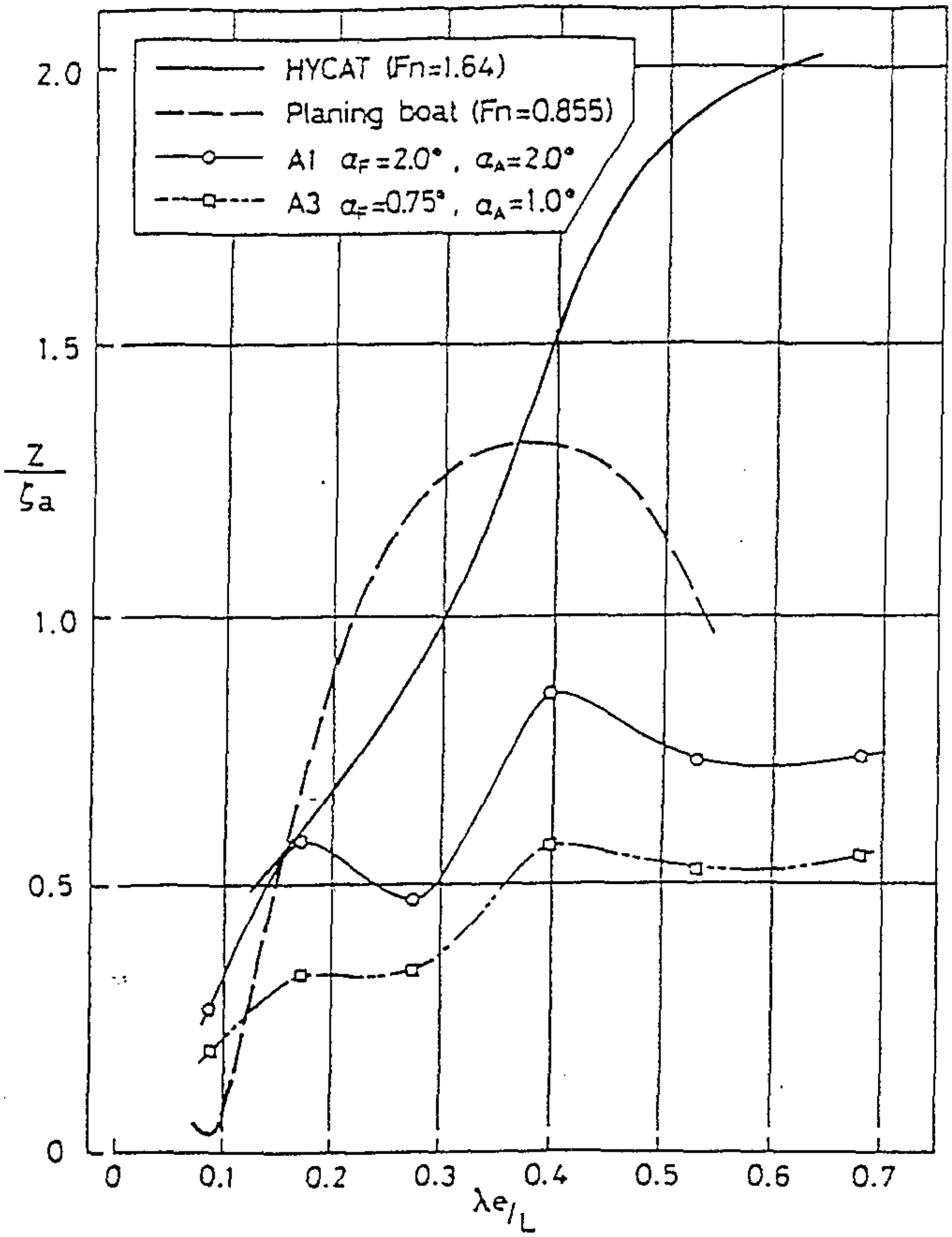

Fig 12. Comparison of heave transfer function (Miyata1989)

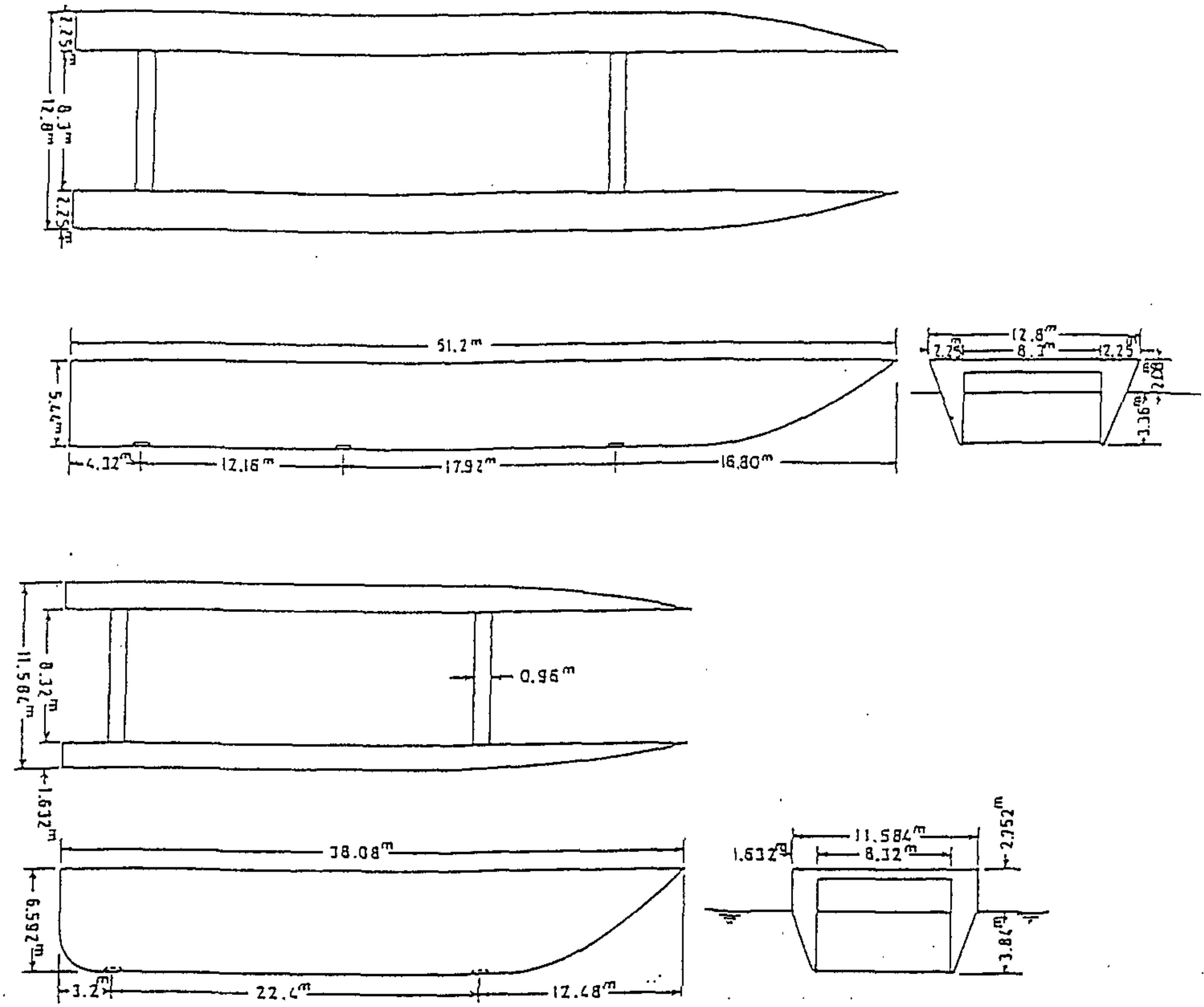

Fig 13. Arrangement of HC 200B hydrofoil