Presentation delivered to the Third International Conference on Fast Sea Transportation (**FAST '95**) in Lubeck-Travemunde, Germany, 25-27 September 1995, by ***Prof.Dr-Ing..K.G.Hoppe***, Mechanical Engineering Department, University of Stellenbosch, Republic of South Africa.

OPTIMISATION OF HYDROFOIL-SUPPORTED-PLANING CATAMARANS

ABSTRACT

A hybrid of a Catamaran with a special hydrofoil system (Hysucat) was developed at the University of Stellenbosch and lead to the construction of about 100 sea-going craft, the largest being 36m with a top-speed of 38 knot. The early designs were optimized by use of systematical model tests. A theoretical method in the form of a computer program is presented and allows more detailed design parameter recognition and further optimization by systematical parameter variation. The theoretical result is approved by model test data and prototype trial data comparisons. The theoretical design prediction is shown to be realistic and the main parameter influence on the hydrodynamic performance is well presented as shown on an example of a 22m Hysucat Ferry, which compares well with Hydrofoil, SES, Hovercraft and Catamaran designs.

1. INTRODUCTION

The hydrofoil supported catamaran (Hysucat) is a hybrid of a planing catamaran and a hydrofoil system, the catamaran offering high initial stability and large deck areas and the hydrofoils giving reduced resistance and low propulsion power.

A fixed wing hydrofoil system with automatic trim stabilization for high speed catamarans has been developed at the University of Stellenbosch, RSA, since 1980, when it was discovered in initial model tests, that resistance reductions of nearly 40% are possible due to such a foil system as proposed by Dr. Hoppe (1982).

Early hydrofoil systems were designed by use of airfoil theory and planing hull data and systematical model testing. Foils and hulls were tested separately and in the hybrid combination. Some systematical model test series were conducted to establish some kind of database.

This way, several Hysucats were designed and about 100 built to date with sizes from 5,6m (1,4t) to 36m (140t). Many already existing catamarans were retrofitted with hydrofoil systems. All Hysucats proved the strong propulsion power reduction and an excellent seakeeping in rough water, see Hoppe (1991,1991a, 1992). For further optimization, a more complete design theory is desired, which allows recognition of the influence of each of the many design parameters involved on the Hysucat resistance in order to enable the designer to choose the best combination of hydrofoil and hull variables. The attempts to establish such a design method shall be presented here.

Prototype trial backfeed data transformed to dimensionless parameters (transport efficiency) allow objective comparisons to conventional craft and indicate that the Hysucat is one of the most efficient and unsophisticated High Speed Light Craft principles.

2. THE HYSUCAT PRINCIPLE

2.1) Hull-Hydrofoil Configuration

The principle hydrofoil system arrangement for a planing catamaran with deep-V-characteristics is shown in Fig.1 and Fig. 2. The main-foil is situated slightly forward of the LCG position and spans the tunnel gap between the fully asymmetrical demi-hulls near the keels.

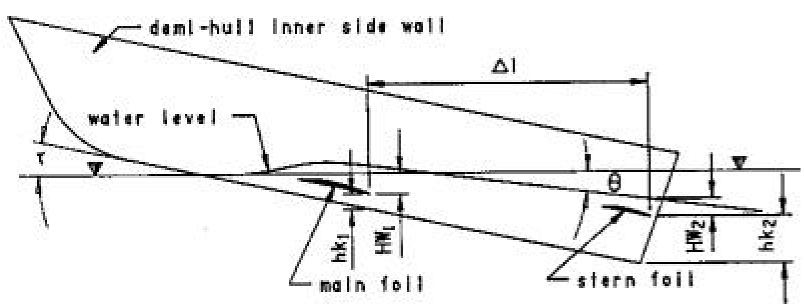


Fig. 1: Hysucat Principle

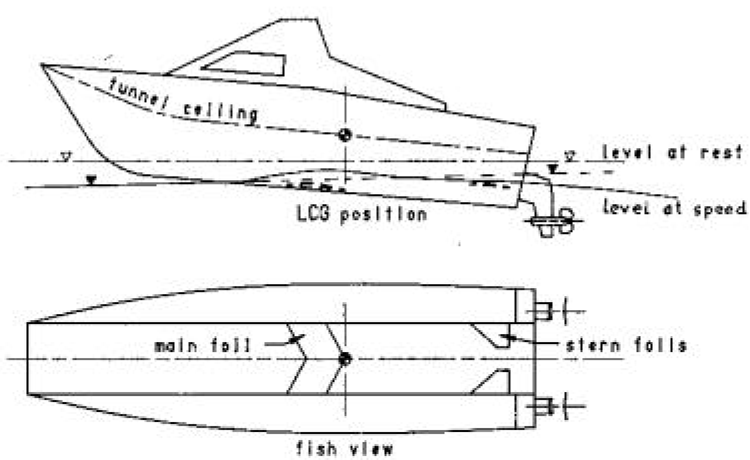


Fig.2: Typical Hysucat Arrangement

The trim foil or two trim foil struts are arranged near the transom a certain distance above the keels in order to have the foils operating at speed near to the water surface. The foil system is self-stabilizing at speed and maintains a favorable trim angle of the planing surfaces. More details are given by Hoppe (1982).

Other hydrofoil systems were developed and the so-called Canard-hydrofoil arrangement after Gerdsen et. al. (1986) has advantages for Hysucats at the lower Froude numbers (larger craft at 30 to 40 knot). In this arrangement, the smaller trim-foil (foils) is forward of the LCG position and the main-foil rearwards of it.

Two ferries (18m and 22m) were built recently in Germany with this hydrofoil system and have proved very efficient craft, see Fig.11 and Fig.12.

2.2) Principle Functioning

The hydrofoils are designed to carry a maximum load at top speed, lifting the demi-hulls partly out of the water. The hulls carry a part load in order to produce sufficient longitudinal-, transverse-, and course stability. At low speeds, the Hysucat weight is mainly carried by buoyant forces whereas at high speed, the foils carry most of the load. At high speed, the hull buoyancy forces are small and the dynamic planing forces dominant.

The magnitude of these physically different lift force components changes strongly with speed. This has a strong influence on the dynamic length stability of the Hysucat, which is compensated for by the special lengthwise arrangement of the foils. At speed, the hydrofoils produce a lifting force L and a drag or resistance force R. The drag-lift-ratio is a foil efficiency ($e = R/L$). Well designed hydrofoils have very low drag-lift-ratios in the order of $e = 0,03$ to 0,05 (higher in surface effect mode).

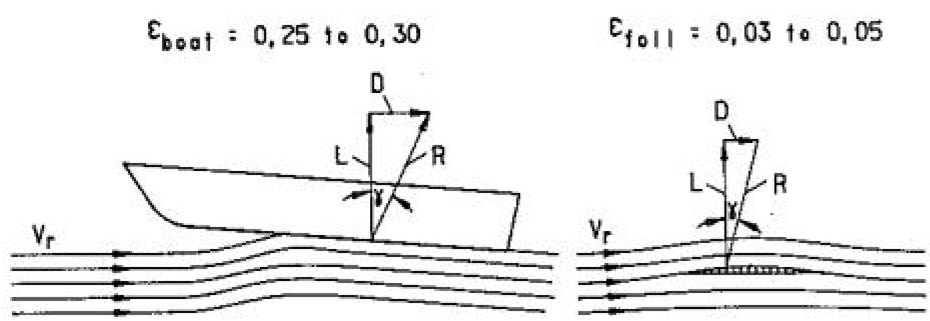


Fig 3: Drag-Lift Ratios

Planing hulls have much higher drag-lift-ratios, about 5 to 10 times larger than one of the foils, see Fig.3. The combination of the hulls with the foils, must therefore, result in a craft with drag-lift-ratios in between the hull and the foil. Such a hybrid will be more efficient than the catamaran. The larger the hydrofoil lift, the lighter the hulls will be and the lower their resistance component. The designer will tend to put as much load as possible on the foils, but, the hulls need some remaining load to keep the craft functioning.

The foil lift is reduced gradually when the hydrofoil approaches the water surface from beneath at increased speeds. The so-called hydrofoil surface effect prevents the hydrofoil from "popping" out of the water at excessive speeds. The foil runs at a certain submergence depth, in which the lift forces and hull lift forces combine to balance the total craft weight D.

The foil resistance increases near the surface and the strength of the foil shall not be excessive, but should rather operate at submergence ratios of $h_w / l_c = 0,2$ for efficient foil operation (h_w = water above foil, l_c = foil chord length). Hysucats with too large foils have increased resistance.

Hydrofoil design calculations follow the theories developed in Aeronautics and in Hydrofoil Craft design, see E.V. Lewis (1988). The lift reducing effect in near-surface-operation has to be included as well as the limitations due to the appearance of cavitation at high speeds.

The circulation around the hydrofoils creates pressure forces, which combine with the pressure field of the planing surfaces with the positive effect that the foils and the hulls work more efficiently. The effective aspect ratio of the foil Ar_{eff} increases due to this interference effect. It is considerably larger than the geometrical aspect ratio $AR = B_f / l_c$, B_f being the foil span.

The foil efficiency increases with aspect ratio. The planing hulls experience a similar improvement. The lift creation of the foil is accompanied by a downwash massflow (induced velocities). For a foil with elliptical circulation distribution and best efficiency, the affected downwash mass is the product of the velocity V and the cross-sectional area of a circle with a diameter equal the foil span, see Hoerner (1975). The larger the downwash mass flow, the more efficient the foil. Fig.4 explains how the downwash mass flow is increased in the Hysucat arrangement. The foil functions more efficiently in the combination with the demi-hulls than if it was free running. By use of the downwash mass flow, the effective aspect ratio of the hydrofoil can be determined.

The Fig.4a also explains that a foil near the surface has reduced lift creation, because the downwash mass flow is reduced (hatched area). The flow interference between hull and foil is a main contributing factor of the high efficiency of the Hysucat.

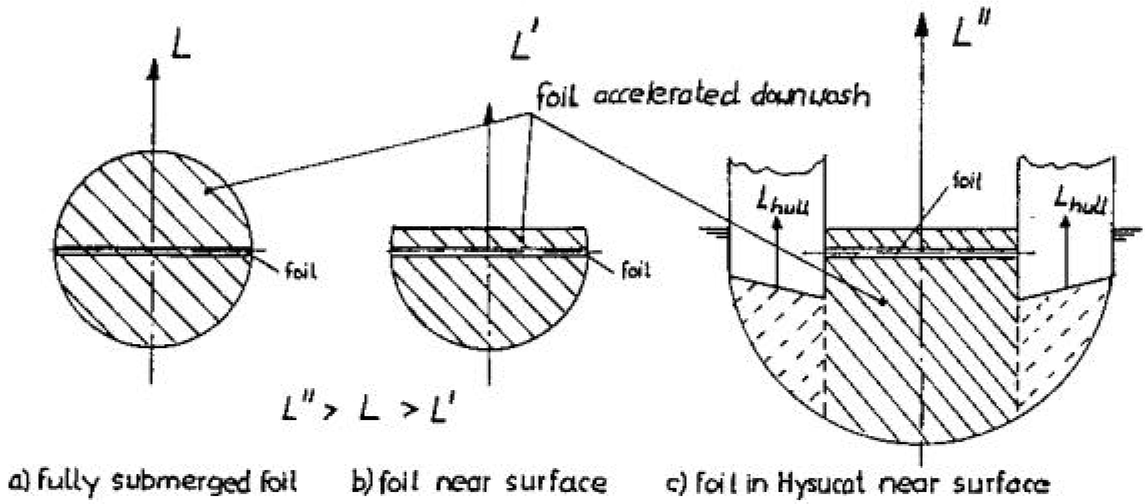


Fig.4: Hydrofoil Induced Mass Flow

The induced velocities of the main-foil pass over the trim-foils at the stern. These foils operate in inclined inflow with a consequential increase in drag. Therefore, the trim-foils are less efficient and are dimensioned to be as small as possible, just right to fulfill the trim stabilizing role. The foil areas are about 25% of the main-foil area.

On slow Hysucats, full span trim-foils are used. For fast Hysucats, the foils become smaller and a single trim-foil spanning the tunnel would not be sufficiently stiff. A middle strut would be needed. Therefore, the smaller fast craft $F_{n?}$ = 3 to 5, are better off with a pair of strut foils.

In sea tests with the 5,6m BMI Hysucat sea model, it was found that a single trim-foil at the stern worked well in flat water, but produced a much harder ride in rough water than with a pair of strut foils.

The hydrofoils in the Hysucat arrangement produce a damping effect at speed in waves as described by Hoppe (1991,1991a,1992). This contributes to the surprising sea-keeping and sea friendliness of most Hysucats in rough water.

The hydrofoils are designed to have a slight sweep angle to allow for smooth wave penetration at high speed when the craft leaves and re-enters the water periodically.

3. THEORETICAL DESIGN DEVELOPMENT

3.1) Early Design Efforts

Early Hysucats were designed by use of planing craft and hydrofoil formulations derived from aeronautics similar to those by E.V.Lewis (1988). The final craft was then optimized in systematical model tests. Several efficient Hysucats were built. For further optimization, more theoretical knowledge was needed to understand hull-foil interference better. A mathematical model was developed.

3.2) Computer Program Hysucat

A computer program to determine the hydrodynamic characteristics of the Hysucat was developed with additional programs for hydrofoil strength and hull stability calculations. The planing hull hydrodynamics are determined by use of the well known Savitsky formulations, see Savitsky (1964) and E.V.Lewis (1988), which were developed for prismatic deep-V-planing hulls and are based upon many systematical model test results. The semi-empirical method allows the lift-and drag forces and center of pressures to be determined in relation to trim, dead-rise angle, wetted length and beam. The catamaran is considered as a deep-V-hull split along the middle length plane and set apart to form the tunnel with straight flat walls between the two demi-hulls. Wetted tunnel areas are included.

The hulls are first considered in a fixed position and the planing lift and drag forces as well as their moments determined. The hydrofoils are then considered with their relative positions to the hulls and to the water-level. Hydrofoil lift, drag and their moments (to transom) are calculated corresponding to the hydrofoil theory for optimal lift distribution (elliptical), corrected for surface effect mode by use of an empirical correction derived in systematical towing tank tests.

The effective aspect ratio of the foils is determined and incorporated in the lift and drag calculations. Plan form correction after Silverstein (1934) and a sweep correction as indicated E.V.Lewis (1988) are added.

The trim-foils in the wake of the main-foil are determined for the corresponding inclined inflow, which results in lower foil efficiencies. For cavitation check-up, the cavitation index as by Du Cane (1972) is determined and printed out. Additional elements as spray rails, keel-beams,stern-wedges or transom flaps, the air-lift of the tunnel ceiling, foil middle strut lift and drag with interference and the craft air drag are determined, mainly by use of formulations derived by Hoerner (1965, 1975). The corresponding moments over transom are calculated.

The initial demi-hull forces are then corrected for the foil-on hull interference, which results in increased planing bottom forces. All vertical force components are summarized and put into relation to the craft weight force vector, which has to balance the forces.

First there will be no equilibrium of vertical forces and a new draught to approach it is interpolated for. Successive iteration calculations give the floating draught for which vertical force equilibrium is reached (craft floating!).

Similar iteration calculations with the force moments and trim angle variation result in the floating trim angle determination. This also includes the propulsor thrust line. Calculations can be repeated for desired speeds, loads and LCG positions of a design proposal. The calculations are controlled by a set of input data. The Hysucat can reach dynamic instability when some foils periodically penetrate the water surface and a porpoising action is observed. The iteration process is then interrupted and no equilibrium postion achievable (endless computations). A counter variable has to stop the program and the design input data have to be varied for new computations.

All design and hydrodynamic parameters are given in the print-out for design revision. By systematical design parameter variation, the minimum effective power is reached, which indicates the optimum combination. However, aspects of practical construction,sea-keeping, course-holding, turning characteristics and stability at all speeds have to be kept in mind by the designer and may limit the free choice of input parameter.

The final total resistance is further corrected for speeds around the so-called hump resistance, where planing effects start to bear by a method as shown by Blount et.al. (1976) as the Savitsky formulations are known to under-predict the resistance in this speed range.

3.3) Verification of Results

The theoretical results were first compared to available model test data and a good agreement was observed for Hysucats with nearly prismatic deep-V-hull shape. For retrofitted, existing catamarans with different hull shapes, the nearest possible deep-V-replacement model had to be established as input for the mathematical model. The model test resistance was then higher than the theoretical result and for the case of symmetrical demi-hulls, it was 20% higher.

A systematic Hysucat model test series was conducted on a 26m Patrol boat design proposal at the Berlin Model Basin (VWS) in 1985 and the correlation of the result to the prototype was recalculated be use of the hydrofoil skin friction correction after Kirkman et.al. (1980) for transitional boundary layer flow. The photograph in Fig.5 shows the simulated top-speed of 46,6 knot with the trim-foils at the stern in extreme surface effect mode.

Comparisons with the theoretical result of Test Series 240 is given in Fig.6 for the model (2,6m) itself with and without calculated air drag. Due to the VWS carriage and photographic equipment in front of the model, the model air drag was very low and hardly measurable. The model test result falls in between the two resistance curves, which indicates that there was probably only a small air drag component and shows a good agreement for practical results. The theoretical resistance of the prototype without air drag is about 5% higher than correlated from the model test in Fig. 7. At this stage, it cannot be stated if the model test or theoretical resistance is more realistic. The proof has to come from prototype trial results.

For the design, the slightly higher theoretical resistance is preferred and air-drag and roughness allowances are added, resulting in the upper resistance curve in Fig.7. The mathematical model allows all detail force components to be determined, which gives the designer more inside understanding of the Hysucat function, which is useful for optimization. The Fig.8 shows drag-lift-ratios e = R/D of the Hysucat with and without foils. The considerable drag improvement due to the foils becomes evident. The Fig.9 shows the four main lift force components and their variation with speed. At 45 knot, the vertical hull force is reduced to less than 35% of the displacement. Fig.10 shows that the drag force components behave in a similar manner. However, hull drag always remains a significant force component at all speeds. The air drag rises fast with speed and streamlining of the superstructure requires serious attention for the fast craft. Many design details can be highlighted by the theoretical results to help the designer in the optimization process.

4. PROTOTYPE DATA

4.1 Design

The design data from test or theory need a prototype allowance to compensate for inaccuracy in the construction, higher surface roughness and additional resistance components such as bolts, corrosion protection electrodes, paint system, water in-and outlets, etc. Other additions are necessary for increased building mass, which after experience with several craft, can be as high as 15% to 30%. LCG positions often need correction.

Diesel engine power is often short by 5% to 10% due to seawater temperature and atmospheric conditions. The hydrofoil surface roughness is a sensitive parameter. Roughness of 0,3 mm can lead to 60% increased foil friction resistance. Waterjet propulsion is well suited due to the low thrust load, but the steering loss in rough weather, especially with an autopilot can be enormous and up to 15%-20% speed loss is possible.
Ventilation can render the waterjet inoperative and this requires careful spray rail and hull design.

Trial runs shall incorporate tuning methods. The Hysucat prototype allowance so far requires 15% power reservation above the theoretical power determination.

4.2 Back-feed Data and Evaluation

Final design approval comes with satisfying prototype trial results, which are rather incomplete for fast, small craft, because of high trial costs in relation to the capital investment. A method to elaborate simple trial runs and evaluate the design was proposed by Dr. Hoppe (1991), by use of the transport efficiency in inversed form:

$$e_p = \frac{1}{\eta_t} = \frac{\Sigma P_b}{\Delta[t] \times 9{,}81 \times v[m/s]} = \frac{\varepsilon}{P.C.}$$

With P_b = total engine brake power, ? = displacement mass in t, e_p = dimensionless power ratio and η_t = transport efficiency, e = total resistance weight ratio and P.C. = propulsive coefficient P_e / P_b.

Comparison of e_p values of different craft or of the trial result data in relation to the design data gives a proper evaluation of the craft efficiency. The lower the e_p-value at the highest Froude displacement number, the lower the power to run the craft at the same mass and speed. Fig.11 shows a graph with e_p-values of about 50 different craft listed by Hoppe (1991) with tendency curves and is suitable to compare a design proposal by plotting the e_p-value on the same graph.

This was done for the Hysucat Ferry “Nordblitz” recently completed by Henze Werft/Baron Yachtbau in Bremerhafen, Germany (see Fig.12). Designed by Hysucat-Engineering-Germany and Judel and Vrolijk/Bremerhafen with a Carnard hydrofoil system by Gerdsen et.al. (1986), the “Nordblitz” is the prototype of a “seabus” for 115 tourists traveling to the North-sea islands. With 54 t displacement and 2 * 690 kW shaft power of the MAN Diesels and a Servogear C.P. propeller, the craft reached 34 knot, which gives an

$$e_p = \frac{2 \times 690 / 0{,}95}{54 \times 9{,}81 \times 34 \times 0{,}5144} = 0{,}157 \qquad \text{(0,95 for gearbox losses)}$$

At $F_{n?}$ = 2,88, which compares well with Hovercraft, Hydrofoil- and SES craft. The e_p-value is plotted in Fig.11.

The design e_p-value with 15% prototype allowance and slightly different conditions (50t, 2 * 820 kW, 37,5 knot) was e_p = 0,173, which is slightly conservative in comparison to the trial result (because of conservative allowance). It presents a reasonable design approval.

CONCLUSION

The Hysucat principle has been presented and a mathematical model for the hydrodynamic design parameter developed. The influence of the main design parameter on the performance becomes clear and allows further optimization. Model test results and prototype trial data are used for the approval of the design method. The design prediction is realistic and several sea-going Hysucats were developed with satisfying trial results.

The use of dimensionless performance parameters (transport efficiency) and comparison to other craft, shows that the Hysucat is one of the most efficient and unsophisticated fast craft.

REFERENCES

Blount, L.B. and Fox, D.L., 1976, "Small Craft Power Prediction", Marine Technology, Vol.13, Nr.1, Jan 1976, pp.14-45.

Du Cane, P., 1972, "High Speed Small Craft", David and Charles: Newton Abbot, pp42-46.

Edward, V. Lewis, 1988, "Principles of Naval Architecture, Volume 2, Resistance, Propulsion and Vibration", pp110-116, SNAME, Jersey City, N.Y.

Gerdsen, H.G and Jabusch,W., 1986, "Hydrofoil Supported Catamaran", European Patent Nr. EPA 0199145 and corresponding overseas patents.

Hoerner, S.F., 1965, "Fluid-Dynamic Drag", published by the Author, 2 King Lane, Greenbriar, Brick Town, N.Y. 08723

Hoerner, S.F., 1975 "Fluid-Dynamic Lift", Hoerner Fluid Dynamics, P.O.Box 342, Brick Town, N.Y. 08723.

Hoppe, K.G., 1982, "Boats, Hydrofoil Supported Catamarans", RSA Patent 82/3505 and corresponding overseas patents.

Hoppe, K.G., 1991, "Performance Evaluation of High Speed Surface Craft with Reference to the Hysucat Development", Fast Ferry International, Vol. 30, Nr. 1 and 3, January and April, 1991.

Hoppe, K.G.,1991a, "The Hysucat Development", Ship Technology Research, Vol.38, 1991.

Hoppe, K.G., 1992, “Hysucat – an all South African Development, The Hysucat Development.”, SA Mechanical Engineer, Vol.42, Nr.10, October 1992.

Kirkman, K.L and Kloetzli,F.W., 1980, “Scale Problems of Model Appendages”, University of Michigan, Ann Arbor.

Savitsky, D., 1964, “Hydrodynamic Design of Planing Hulls”, Marine Technology, Vol.1, October 1964.

Silverstein, A., 1934, NACA Report 502, Fig.7.

7. FIGURES

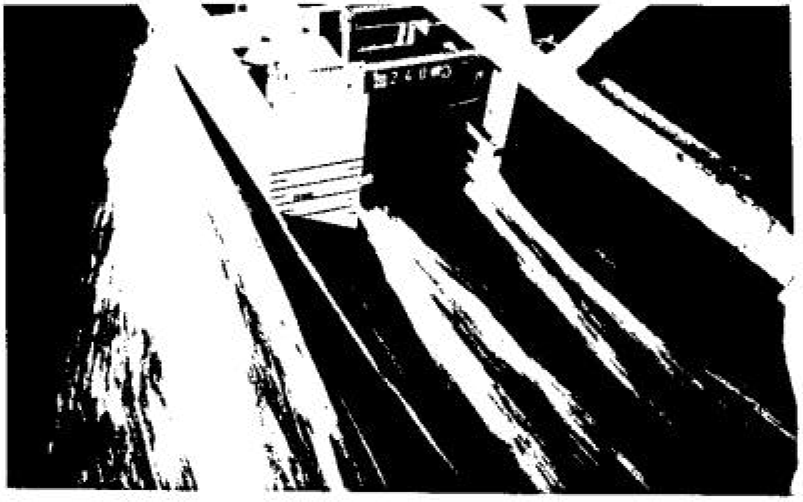


Fig.5: Hysucat Model at simulated 46,6 knot, Sternfoils in extreme Surface-Effect-Mode

Hysucat 26 Model
Resistance:Theorie and Test
Simulated 110 t, 0.38•Lc LCG

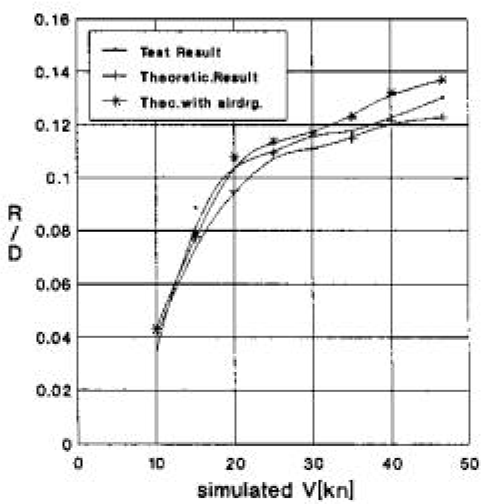


Fig.6 Model Resistance Comparison

Hysucat 26 Prototype
Resistance:Theorie and Test
Displ.= 110 t LCG=38% Lc

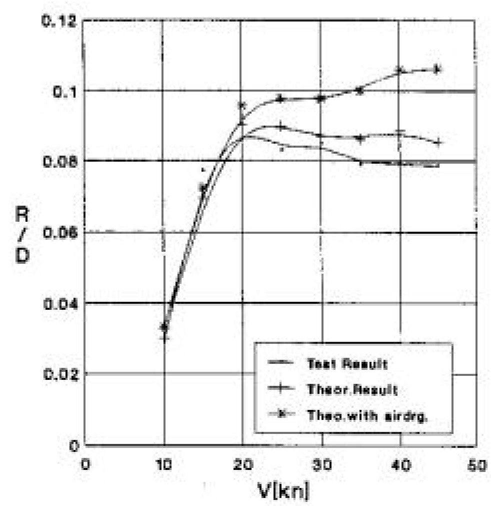
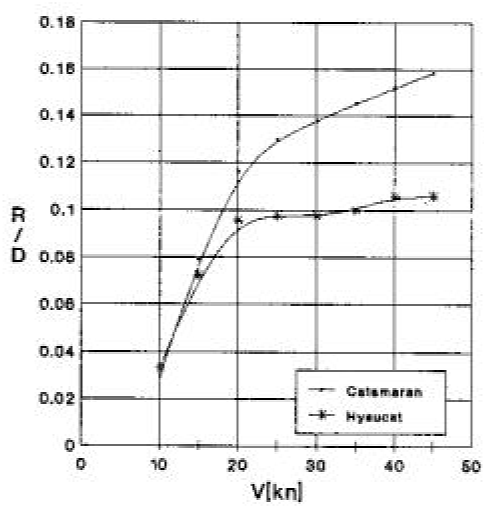


Fig.7 Prototype Resistance Comparison



Hysucat 26 Prototype
Drag of Hysucat and Catamaran
Displ.= 110 t LCG=38% Lc

Fig.8 Prototype Resistance Comparison

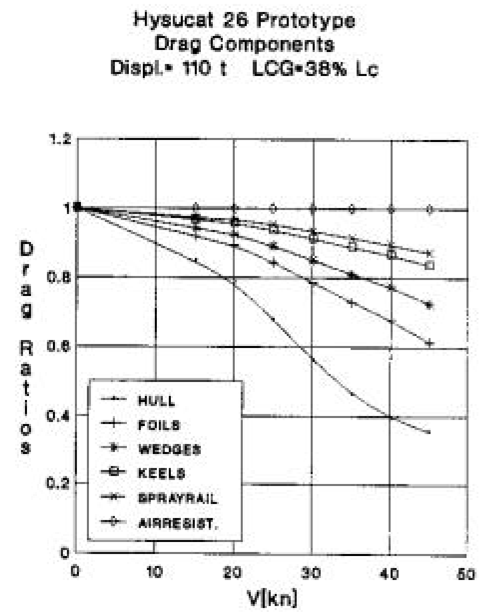


Fig.10 Drag Components of Hysucat

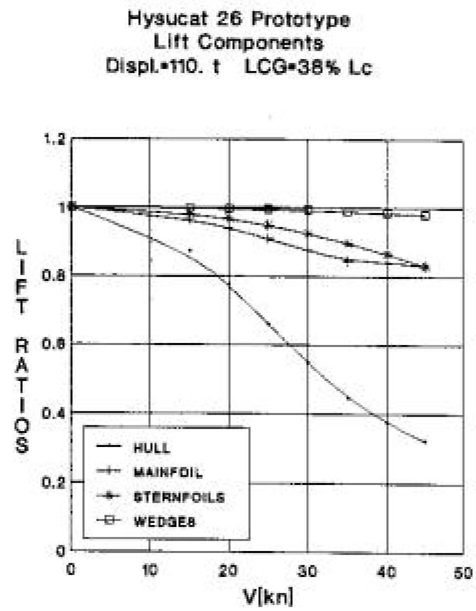


Fig.9 Lift Components of Hysucat

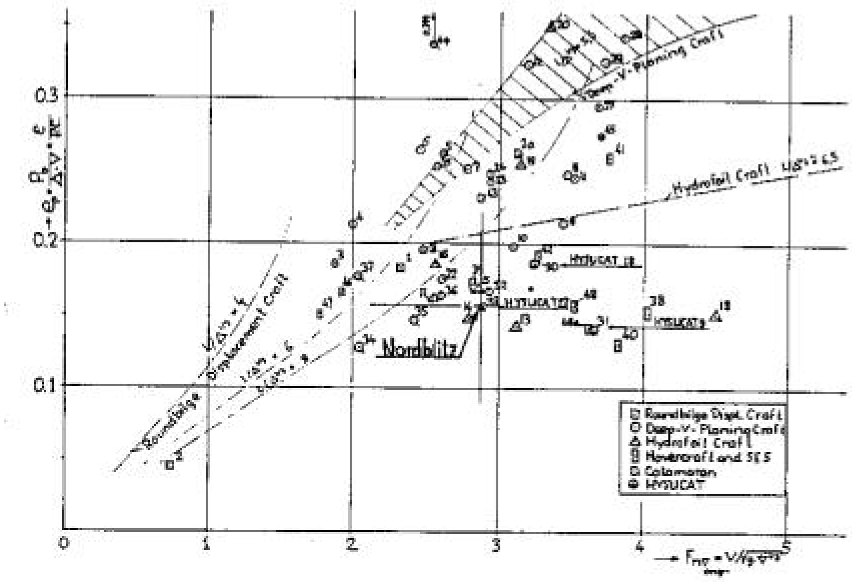


Fig. 11: High-Speed-Surface Craft Power Ratios e_p

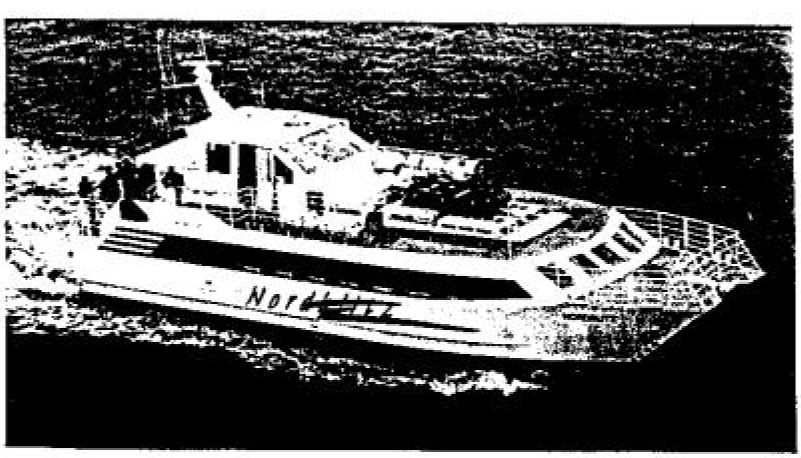


Fig. 12: Hysucat Ferry "Nordblitz"