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High Speed Marine Vehicle Development[1]

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Abstract

Over the past decade, high speed catamarans have displaced conventional passenger and car ferry craft. This paper discusses this as the introduction of advanced concepts in marine vehicles. These developments follow from new technologies and involve hybrid craft designs.

This paper summarizes these designs can be discussed in terms of hydrodynamic and hull structural research and development.

NOMENCLATURE

B	Beam, overall
b	Demihull beam
BHP	Propulsion brake horsepower
C_b	Block Coefficient
C_{pb}	Demihull prismatic coefficient
Fn, F_∇	Froude number
g	Acceleration due to gravity
K	Speed coefficient
L	Length
Q	Powering Coefficient
s	Catamaran separation distance
T	Draft
V	Velocity
V_S	Velocity, knots
Δ	Displacement

1. BACKGROUND

Recent, advances in computers, material science, and software, have enabled naval architects to design 35-50 knot catamarans[1,2,3]. These high speed craft operate at Froude numbers Fn.>0.35 as shown in Fig. 1. They can be competitive with helicopters and aircraft over 100 to 1000 km routes. Presently catamarans are being marketed by Europe and the Pacific Rim countries (Japan and Australia). There is also interest in the United States in such high speed marine craft.

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2. TECHNOLOGY CROSS FOR HIGH PERFORMANCE

Since today's marine technology represents both traditional and new technologies, it became necessary to select a vessel type among the high performance marine vehicles [1]. These include high speed mono-hulls, hydrofoils, air cushion vehicles, surface effect ships, displacement catamarans, and wing-in-ground-effect (WIG) vehicles. It is important to identify where performance breakthroughs can be realized. This can be best understood from a comparison of two earlier high performance vehicle designs: the China Tea Clipper Ship of the 1850's and the Japanese Zero fighter plane of the 1930's. Both vehicles achieved high performance by the careful merging of materials, structure arrangement, and low drag form around an efficient propulsion system (Table 1). This can be termed the Technology Cross shown in Figure 2. Performance breakthroughs can occur through the integration and development of the technology cross. These four technologies include:

I. Use of strong lightweight materials.
II. Rational estimation of loads and design of an optimum structure
III. Adoption of low drag, seakeeping and maneuverable form.
IV. Use of efficient propulsion/ maneuvering systems.

2.1 EXAMPLE I: THE CHINA TEA CLIPPER

On March 20th 1864, the British press announced that the clipper ship "Zingra" completed its record voyage of 85 days from Shanghai to Liverpool [4]. The wooden tea chests, were quickly unloaded and sold. In order to achieve this breakthrough in speed, the designer selected a fine hull form around these tea chests. They also obtained Lloyds Classification Society approval to use wooden frames with iron braces. The masts were also reinforced with iron and the sails were secured for the long voyage by wire. The Zingra and her sister clipper ships provide us with a clear example of how high performance ships can be designed based on the Technology Cross.

2.2 EXAMPLE II: THE ZERO JAPANESE FIGHTER PLANE

On the second day of the Pacific war, December 8, 1941, a group of bombers escorted by Japanese Zero fighter planes bombed Clark and Iba air bases in the Philippines 865 km from Japanese bases on Taiwan (1700 km round trip). Because 1940 era fighter planes had only a 1500-1600 km range, the US intelligence reported the JNAF Zeros had bombed the Philippines from aircraft carriers.[5]

The Zero designer Jiro Horiskoshi had achieved a performance breakthrough. The Zero had a 3110 Km range flying at 500 km/hr. Horikoshi integrated the cockpit and wing spar, and retractable landing gear. Special attention was given to the surface finish and the use of aerodynamic streamlining. In contrast to the heavier air frame and higher powered engines in US aircraft, the Zero was designed to a 2,250-2,750 kg weight with a relatively small 950 hp engine. By the end of hostilities in 1945, a total of 10,815 Zeros had been produced. Today there remain 30 on exhibit [5]. Nevertheless, by 1945 the 900 km/hr jet plane, had already been flight tested.

2.3 EXAMPLE III: THE InCAT

In 1990, the InCat catamaran built in Australia crossed the Atlantic at record speed of 35 knots. This speed record was set by a 78 meter long aluminum displacement hull, powered by twin 4000 hp waterjet units. Similar to the clipper ship design and the Japanese Zero, the InCat performance comes from an emphasis on a lightweight, strong structure coupled with a compact and efficient propulsion system. It is obvious from Table 1 that each performance improvement occurs when the designer follows the Technology Cross.

3 DEJAVUE: THE CATAMARAN - THE CLIPPER SHIP OF THE 1990's

Over 150 years ago, when the industrial revolution began, engineers replaced wind and muscle power with machine power. Steam engines were built to propel ships and trains. Shipbuilders began to debate the question: ***"Why burn expensive fuel to propel the ship instead of using relatively cheap sail (wind) power?"*** In the face of steam engines, a group of shipbuilders concentrated on refining traditional shipbuilding technology to build the 16 knot China Tea Clipper. The 16 knot record speed exceeds the recent America's Cup boat speeds of 12-13 knots.

Today we are in the midst of the information revolution. Computers and databases are used to replace humans doing routine mental operations. A new question has emerged among ship designers: ***"Why burn expensive fuel to elevate the ship hull above the water, when traditional ships simply float on the surface?"*** The answer is to achieve high speed. Nearly three decades ago, high speed passenger hydrofoil vessels began operation on the Soviet Union's rivers and the US Boeing Jetfoil was marketed worldwide. These hydrofoils were followed by a number of passenger carrying air cushion vehicles and surface effect ships.

In spite of these newer vessel concepts, Australian and British shipbuilders continue to deliver high speed aluminum hulled car/passenger displacement catamarans. In a manner of speaking, these catamaran are the clipper ships of the 1990's. The parallel developments of the industrial and information revolutions are illustrated in Figure 3.

3.1 HYDRODYNAMIC DEVELOPMENT OF HIGH SPEED CRAFT

The evolution of high speed craft is a study in marine hydrodynamics. There are four design branches which are shown in Fig. 4 based on the displacement Froude number F_∇ [6].

Branch I - Displacement craft $0< F_\nabla < 1.5$
Branch II- Air Cushion Vehicles $2.5< F_\nabla<6.0$
Branch III- Planing Hull $2.5< F_\nabla<6.0$
Branch IV-Hydrofoil Craft $2.5< F_\nabla<6.0$
Branch V- WIG-Ecranoplane $8.0< F_\nabla<11.0$

The displacement hull speed is limited due to its large wave resistance at $F_\nabla=1.5$. To overcome this a number of hybrid craft have been introduced a hybrid mode $1.5<F_\nabla <2.5$. These craft are illustrated in Fig. 5. This figure shows that the hull block coefficient decreases as the speed increases. This is a branching where with multi-hull displacement craft the block coefficient based on overall beam becomes small. This dashed line is the high speed catamaran, trimaran and quadmaran.

3.2 RESISTANCE CONSIDERATIONS FOR HIGH SPEED CATAMARAN

A number of researchers[7,8] have provided guidelines for the Catamaran design. In addition to hull form, they found the resistance is sensitive to the hull separation s to demi-hull beam b, s/b ratio. These guidelines include :

1. The resistance of an unsymmetrical demi-hull is often higher than an equivalent symmetrical hull at $F_n>0.5$.
2. When the catamaran operates at $F_n > 0.5$, the resistance of an unsymmetric hull becomes lower than an equivalent symmetrical.
3. The wave system interference between two demi-hulls is related to the separation distance s. s/b = 6 is considered the minimal separation for non-interference.
4. The theoretical/experimental results show that the Froude number at which there is a positive demi-hull interface is given by,

$$F_{ro} = 0.55 + 0.042\left[\frac{\Delta}{(0.1L)^3}\right]^2\left[\frac{0.166}{\left(\frac{s}{b}-4\right)^{\frac{7}{4}}}+1\right]^2 \quad (1)$$

5. At higher Froude numbers, there is a flow blockage between the catamaran hulls. Experiments have shown this occurs at,

$$F_{rb} = \sqrt{\frac{10}{\frac{L}{b}\left(\frac{s}{s-c_{pb}}\right)^2 - 1}} \quad (2)$$

The results for a number of high speed catamarans are surveyed in Figure 9. This figure shows that these catamarans operate at design Froude number Fr,

$$F_{ro} < F_r < F_{rb} \quad (3)$$

Typically $\frac{F_r}{F_{ro}}$ is in the range of

$1.1 < F_r/F_{ro} < 1.4$.

The hydraulic jump occurs in the range of $2.0<Fn<2.5$ [3].

Returning to Fig. 5 for $F_\nabla>1.5$, the other approach is to adopt designs based on hybrid craft such as:

1. Semi-displacement craft
2. Semi-submerged craft
3. Air cavity craft

Then at $F_\nabla>2.5$,dynamic lift supported craft are typically the preferred design.

4.0 ACHIEVEMENT OF HIGH SPEED CRAFT

There is a strong interest in 40-50 knot marine transport craft. Table 2 summaries several recent developments[9-11]. In each case the requirements for a high speed craft is being fulfilled by a hybrid craft such as an SES or Hydrofoil SWATH. The consequence of this development is the improvement of the design of high speed craft. It is useful to compare the state of the art in 1970 and 1995. Figure 6 shows the results of a survey of high speed craft which are plotted on the basis of:

Power Coefficient:

$$Q = \frac{0.148\ BHP}{\Delta\ V_s} \quad (4)$$

Speed Coefficient:

$$K = \frac{0.583\ V_s}{\Delta^{\frac{1}{6}}} \quad (5)$$

The performance line of 1970 has been broken by the current designs as shown in Fig. 6. The lower 1995 performance line shows a significant improvement in the power coefficient and the speed coefficient. This reflects improvements in both hydrodynamics and the use of lightweight, high strength hull structures.

5. LIGHTWEIGHT STRUCTURE CONSIDERATIONS

In addition to the hydrodynamics it is necessary to return to the technology cross and consider material and structure design. This has resulted in the development of a lightweight ship structure test rig and an integrated finite element analysis approach[12].

The structure test rig is 6.1m long x 3.05m wide x3.05 high with six 222 KN (50,000 lb) force actuators. The test frame is shown in Fig. 7. It was used in the tests of a 4.6mx1.52m (15x5 ft) aluminum hull test panel for a 40-45 kt 40m craft. The test results were validated the finite element analysis. By optimization of the panel design, selecting a thinner plate and adding an additional longitudinal, a weight reduction of 15% was achieved [12]. This reduction in structure weight offsets the increased production man-hours resulting in a net savings.

This test facility is now part of a number of current and future lightweight hull structural tests.

6. CONCLUDING REMARKS

While there are a number of advanced concepts in marine vehicles, the present work shows that they can be viewed as designs which are attractive in different speed ranges. This view is the basis for the following conclusions:

1. There is a parallel traditional/new technology available for high speed craft.
2. Performance breakthroughs occur from the integration and development of the technology cross quadrants.
3. The resistance of an unsymmetrical demi-hull is often higher than an equivalent symmetrical hull at $F_n < 0.5$.
4. When the catamaran operates at $F_n > 0.5$, the resistance of an unsymmetric hull becomes lower than an equivalent symmetrical hull.
5. The wave system interference between two hulls is related to the separation distance s. s/b = 6 is considered the minimal separation for non-interference.
6. The theoretical/experimental results show that the design should operate at a Froude number F_{na} where there is a positive demi-hull interface.
7. At a higher Froude number F_{nb}, there is a flow blockage between the catamaran hulls. This causes a hydraulic jump which significantly increases the and the resistance increases significantly.
8. For economical operation, the catamaran should operate at design Froude number Fn,
$$F_{no} < Fn < F_{nb}$$
9. The achievement of high performance also requires attention be given to the design of lightweight, high strength hull structure using both Finite Element Analysis and Structural tests.
10. The introduction of the 6.1x3.05x3.05 structural test frame has created an important tool for the development of lightweight hull structures.

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Table 2 - Recent examples for 40-50 knot hydrofoil

No.	Project	Sponsor	Vessel	Type	Payload ton	Range naut mi.	Speed kts	Sea state max.	LBT m	Ref.
I-a	Techno Superliner	JAPAN	Air Cushion Catamaran	Hybrid (Hisho)	1000	500	50	6	127x27x1.4	[9]
I-b	Techno Superliner	JAPAN	Hydrofoil SWATH	Hybrid (Hayate)	1000	500	50	6	72x37x5.6	[9]
II-a	MDV Hull Deployable	US Navy	SES	Hybrid	-	2000	45-50	5	53x14x0.6	[10]
II-b	MDV Hull Deployable	US Navy		Hybrid	-	2000	45-50	5	39x14x2.7	[10]
III	FAST	MARIN	SES	Hybrid	2000 pass. 250 cars	350	42	-	-	[11]

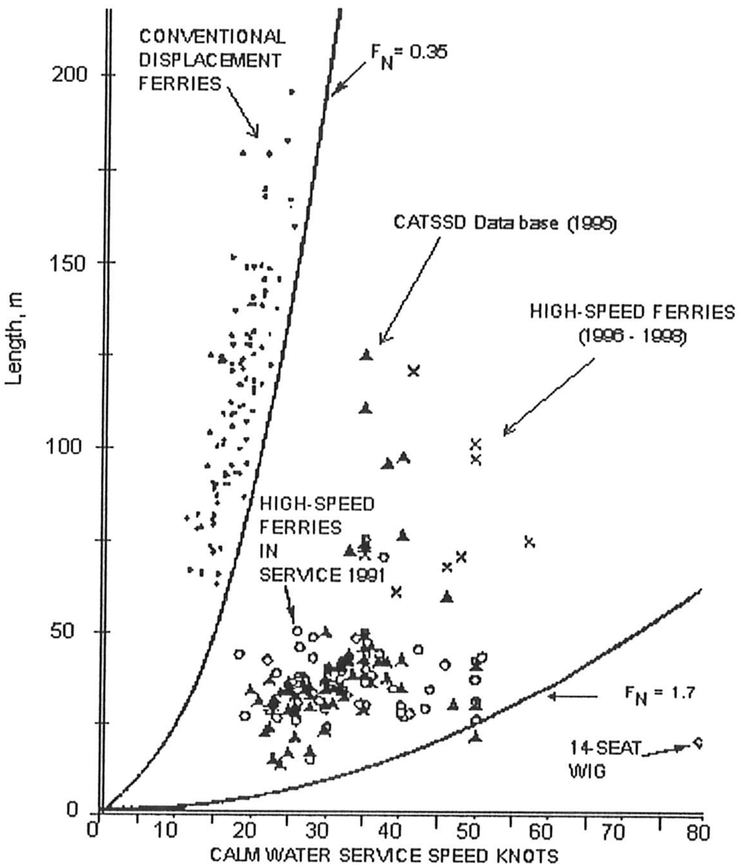

Fig. 1
Comparison of ship length versus speed for passenger ferries 1991 - 1998[3)]

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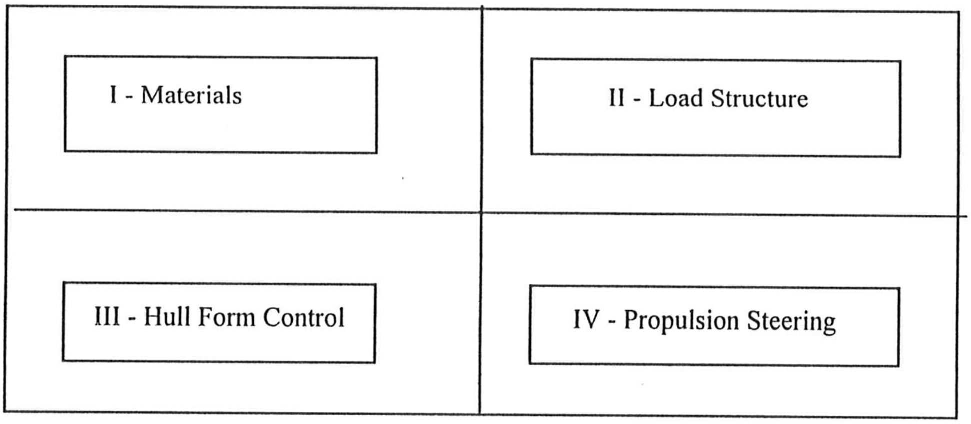
Table 1 - Comparison of High Performance Vehicle Designs[3]

	Clipper Ship	Japanese Zero	Passenger Catamaran
Item	Sailing Ship (1850)	Fighter Plane (1937)	Ferry Craft (1988)
Goals	Speed Endurance Economy	Speed Maneuverability Range	Speed Seakeeping Economical Operation.
Constraints	Wood	Small Engine	Displacement hull
Focus	Hull Strength Cost	Exceed State of Art	Weight/Propulsion Cost
Strategy	Utility Design	Clean Design with small engine	Optimum Cat Design
Predecessor	Sailing Ships (1850)	Type 96 "Clude" fighter (1930)	Catamarans (1970)
I. Material	Composite wood / Iron	Duralumin (7075 Al)	Aluminum
Note	Weight/Strength Improved	30% Higher Tensile 80% Higher Yield	Extrusions to reduce welds
II. Loads Estimate	Classification Society	Rational Design	Classification Society
Structure		Navy Spees	
Note	Longitudinal /Frame	Integral Wing Cockpit	Strength Deck Separate House
III. Form	Slender	Streamline	Stream line/Slender
Note	Special Bow	Enclosed Cockpit Retractable Landing Gear	Good Seakeeping Form
IV. Propulsion	Large Sail Plan	Special Wing Section Special Propeller	Steering Waterjet
Notes	Wires Used for Sail Rigging	Air Cooled Lightweight Engine	Lightweight High Speed Diesel Engines

Fig. 2
Technology cross



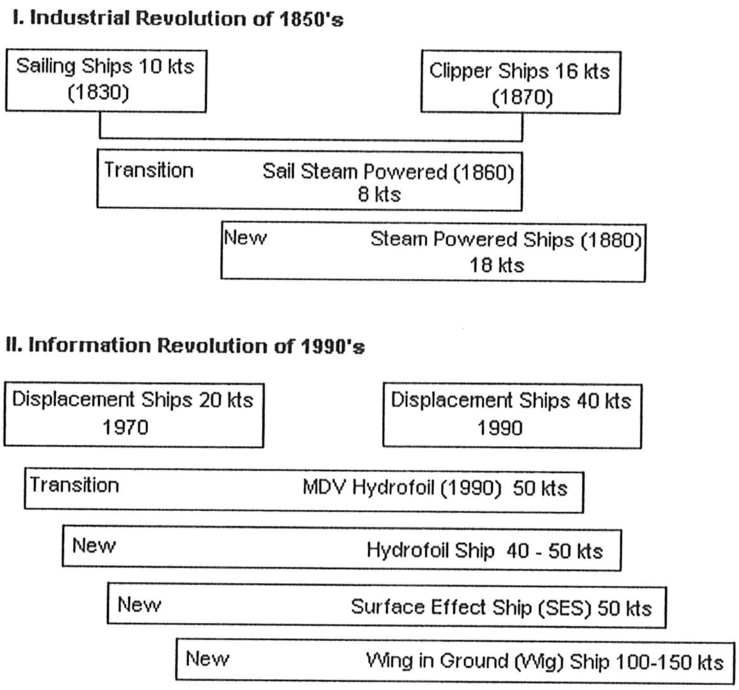


Fig. 3
Parallel technology development Industrial/Information Revolutions[3]

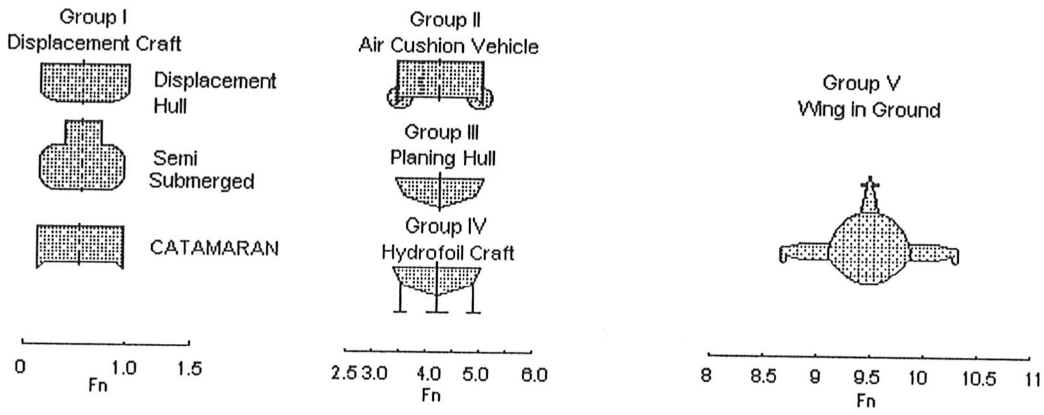


Fig. 4 High Speed Marine Vehicle Design and Froude Number[6]

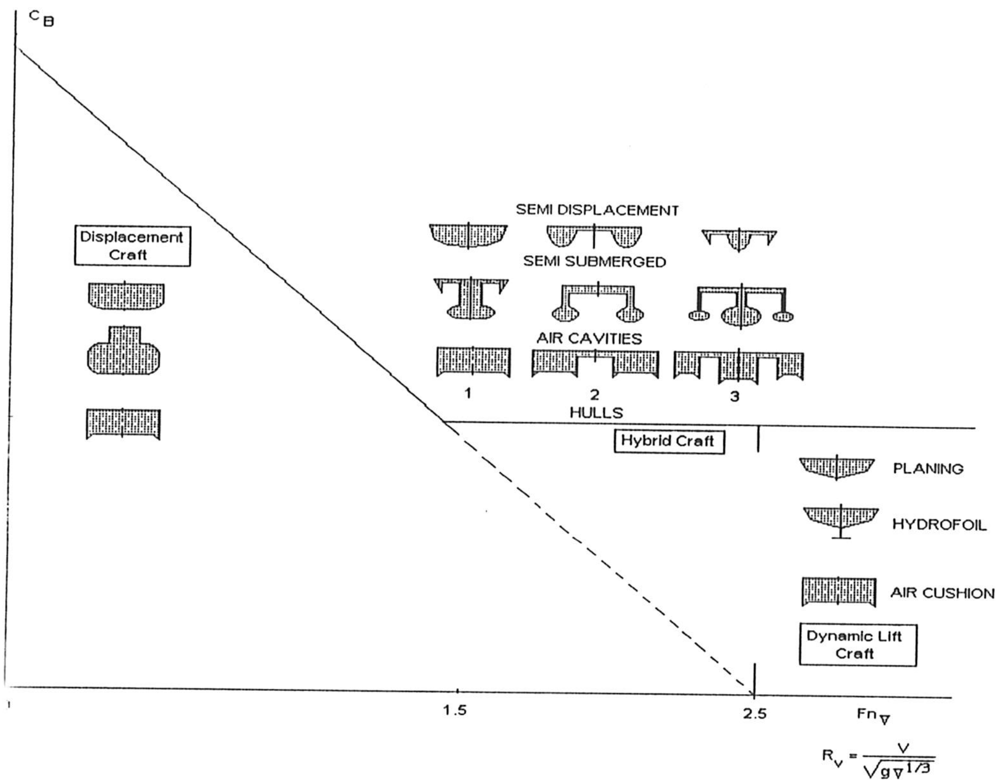


Fig. 5 Development of Hybrid Craft[6]

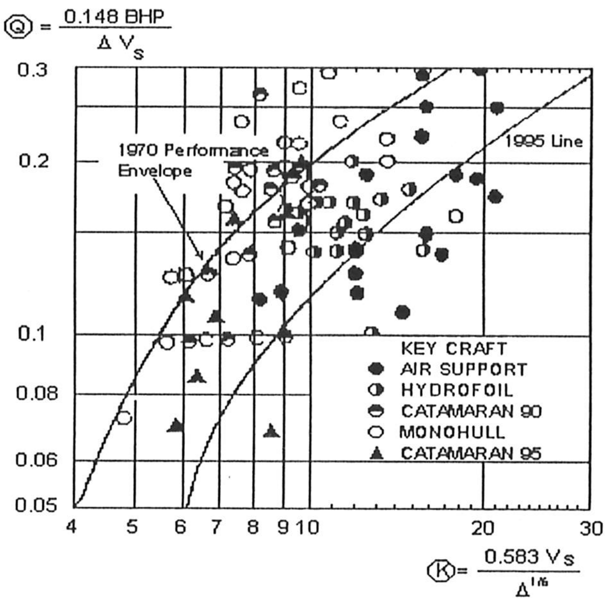


Fig. 6 Comparison of 1970 and 1995 High Speed Craft Performance[3]

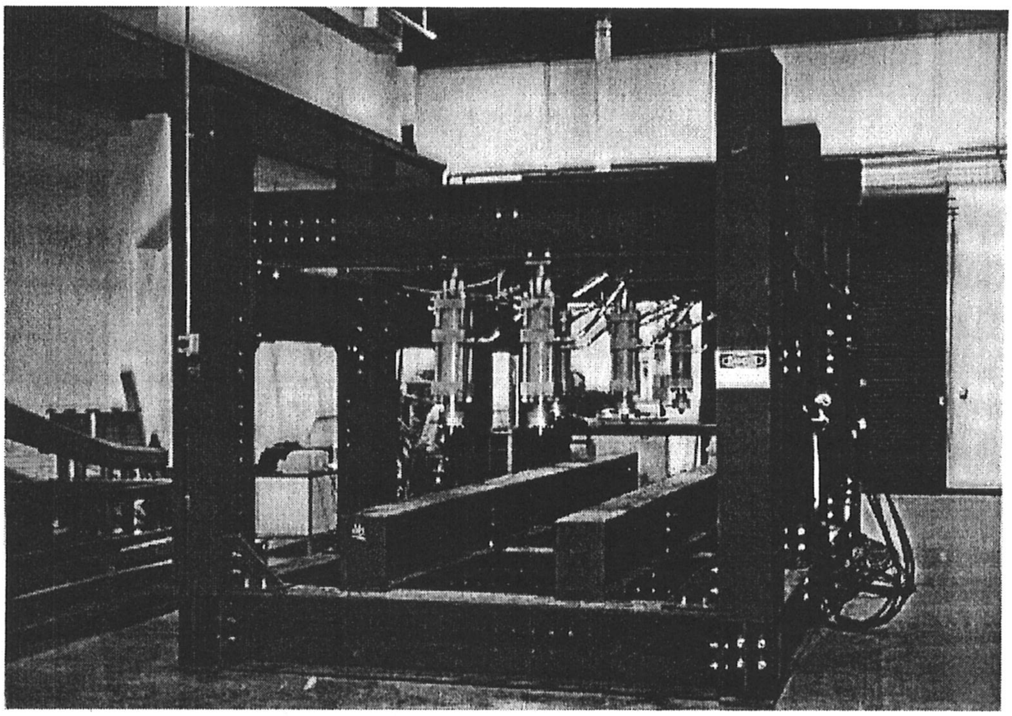


Fig 7. 6.1x3.05x3.05 m UNO Structural Test Frame