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Hydrofoil Hullform Section

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HYDROFOIL HULLFORM SELECTION

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Abstract

Historically the selection of a hydrofoil hullform has been dictated primarily by design considerations related to foilborne performance. Emerging mission requirements for future hydrofoil ships place greater emphasis on the total vehicle performance both hullborne and foilborne. The selection of the hydrofoil hull and the design features are discussed as well as established features of existing and future hydrofoil hulls. It is demonstrated that while hydrofoil hulls must satisfy requirements unique to the concept, satisfaction of the requirements follows traditional naval architectural practice, and generally results in hullforms similar to conventional naval platforms of comparative size.

I. Introduction

The hydrofoil hullform requirements can be grouped generically into five topical areas. First the hull together with the superstructure must provide the containment for the internal systems of the craft and the operating crew. This obvious requirement together with the primary hydrodynamic considerations; hullborne speed, take-off transition to foilborne operations, and wave-impact concerns while foilborne, provides the major definition for the general overall size of the hull. Second, hydrofoil unique design features; namely load distribution matching between hullborne and foilborne conditions, lift system retraction, and optimum take-off performance generate further definition of the hullform. Third, a host of further requirements related to the mission of the craft provides more definition of both the hullform and the overall arrangement of the configuration; both internally and externally. These include, hullborne speed and seakeeping, weapon system arrangement, stability and subdivision, fuel tankage, lift system retraction necessity, and foilborne and hullborne maneuvering.

Two additional topical areas, hullborne propulsion and structural considerations, must be addressed as they interplay with the hullform to influence the total hydrofoil craft design, principally in the desire to minimize overall weight.

In this paper, prime emphasis will be devoted to the first three topics; General Containment Considerations, Hydrofoil Unique Design Features, and Hydrofoil Mission Related Features. Hullborne Propulsion and Structural Considerations as discussed will focus on experienced and expected trends for future craft.'

Before proceeding, it is of interest to describe the hullform requirements emphasized in some U.S. hydrofoil designs over the past two decades. Generally as the concept has matured from developmental to operational status, the hull designer has been able to shift his prime attention from assuring basic foilborne operation to the more total picture of balancing the design to suit the intended mission of the particular craft.

The prime hull design emphasis on the H. S. DENISON, Figure 1, delivered to the U.S. Maritime Administration in 1962; was achieving foilborne operation. The aerospace seaplane experience is clearly seen in the hullform. Early design studies included a stepped hull, which was not discarded until just prior to construction.

The overall arrangement precluded any modifications to demonstrate other missions. Although in all fairness, her prime mission was to demonstrate open ocean operations, which she was the first to do; and very successfully. The DENISON'S hullborne propulsors were waterjets to minimize take-off drag. Hullborne propulsion, volumetric and hull structural weight efficiences were low by today's criteria. Stability with the foils retracted was notoriously poor, and when her flooding subdivision was tested on a North Carolina river shoal, she was saved from sinking by the shoal itself.

Design of the PLAINVIEW AGEH-1, Figure 2, was initiated in 1961. PWISVIEW was planned as a two-stage development program with a fifty-knot initial foil system, to be followed by a ninety-knot system. Pri-

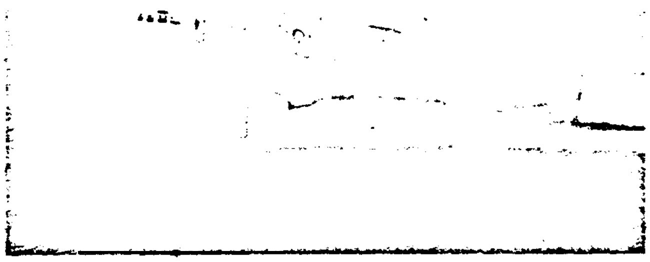

Fig. 1 U. S. Maritime Administration • H. S. Denison

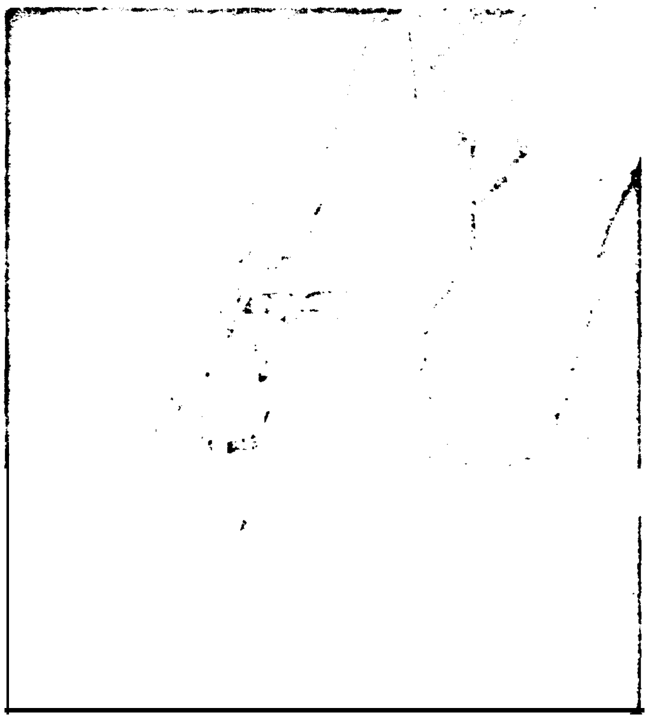

Fig. 2. U.S. Navy · AGEH-1 Plainview

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mary emphasis on the hullform design was to support the ninety-knot design objectives. Retractable outdrives were ultilizied for hullborne propulsion; again to minimize take-off drag. While her structural weight efficiency is high, the use of a 90/10 "conventional" configuration for the foil system distribution, precluded high volumetric efficiency. This coupled with the amidship location of propulsion machinery (dictated by the ninety knot requirement) introduces some difficulties in the utilization of her payload capabilities and limits her military usefulness.

However by virtue of her size, the largest operational hydrofoil in the world, PLAINVIEW is a vital asset to future hydrofoil development.

Two Patrol Gunboat Hydrofoils (PGH) were authorized in the FY 1966 shipbuilding programs. PGH-1 FLAGSTAFF, Figure 3, was designed and built by Grumman Aerospace Corporation, and delivered in 1968. TUCUMCARI, PGH-2, was designed and built by the Boeing Company and delivered in the same year.

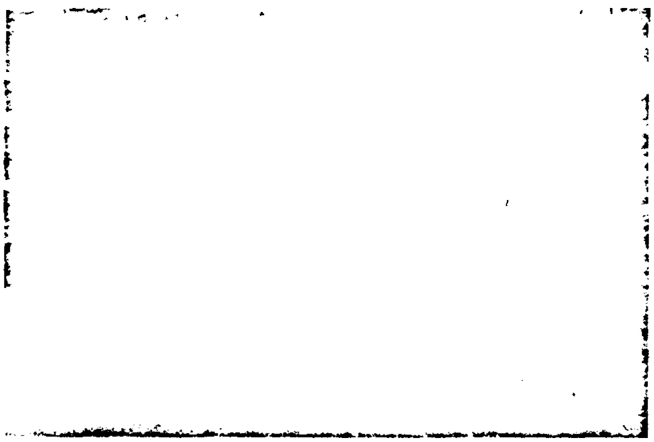


Fig. 3 U. S. Navy - PGH-1 Flagstaff

FLAGSTAFF, has a 70/30 "conventional" foil system distribution and a foilborne propulsion system consisting of a single variable-pitch propeller located on the aft pod. The propeller is driven by a zee-drive transmission. TUCUMCARI has a canard foil system with a 31/69 load distribution. The foilborne propulsion system consisted of a single waterjet pump located in the hull with water inlets in the lower end of each main (aft) strut.

Both craft used waterjet propulsion during hullborne mode to minimize take-off drag. The craft were relatively short in length due to an overall hoisting length restriction of 65 feet imposed during design studies conducted prior to authorization. As a result of these early design studies hullborne speed requirements were low, although a relatively high hullborne endurance was specified.

The short overall lengths coupled with stringent intact stability requirements resulted in relatively beamy craft with high volumetric efficiencies. Structurally FLAGSTAFF was about 20% heavier on a density (lbs/ft^3 of enclosed volume) basis, owing to the fact she wad designed for series construction from the outset, and also was not subjected to the weight sensitivities inherent in the waterjet powered TUCUMCARI.

The weapon suite for both craft were identical, and although somewhat unsophisticated by today's standards. influenced the arrangements of the craft to a large extent.

PHM-1 PEGASUS, the navy's newest hydrofoil, was authorized in the FY1971 budget, and a sole source contract was awarded to the Boeing Company Cor design and construction. Construction of a sister ship, HERCULES, has been suspended pending a production decision for the class.

The intended mission of the PHM greatly influenced her hullform selection and general arrangement. While the primary emphasis in operation is in the foilborne mode, greater attention was directed to relatively high hullborne speed in the design stage to maximize overall effectiveness for her intended missions. The hullborne speed requirement coupled with Cull forward and aft foil system retraction, which reduces the intact stability design requirements, resulted in a hullform with a moderate length-to-beam ratio of about five to one.

The modern sophisticated weapon suite selected for the PHM was adequately integrated in the overall arrangement. Resulting volumetric and structural efficiencies of the design were in keeping with the developing trends for hydrofoil craft.

II. General Containment Considerations

Recent studies, (1), trended the vehicle densities (full load weight/total enclosed volume) for six prototype hydrofoils; and for six recent design studies developed at NAVSEC and Grumman Aerospace Corporation, Figure 4. A measure of the efficient use of hull structure is the value of vehicle density (full load weight/total). For existing hulls, vehicle densities have generally increased with the maturing of the hydrofoil concept. Early USN R & D hydrofoils had low vehicle densities, while the most recently launched, the PHBI, has a vehicle density on the order of 15 lbs. /ft. 3. This latter value compares favorably with naval displacement vehicles of the destroyer escort type which have densities on the order of 20-22 lbs. /ft^3. Heller and Clark, (2), attribute about 3 lbs. /ft.3 difference in density to the use of all aluminum hulls in hydrofoils versus steel in conventional ships. Use of lighter weight equipment for foilborne performance considerations together with the smaller displacement of hydrofoil vehicles up until this time would account for the remaining differences in densities from conventional naval escort platforms,

While it is difficult to quantify correct or acceptable values for vehicle densities, some keys are offered in terms describing existing hydrofoil vehicles. Operating crews, who must live on, operate, and maintain the crafts use the terms spacious, comfortable, tight and cramped; while designers use terms like efficient, com-

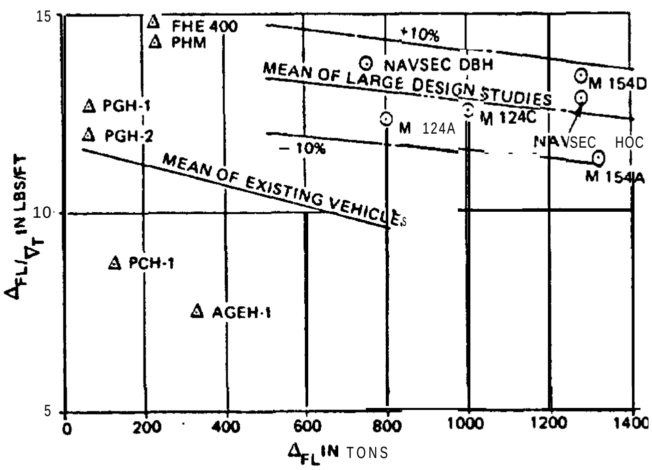


Fig. 4 Vehicle density - based on full load displacement

pact, and under-utilized. Of the prototype vehicles the AGEH is generally recognized as the most spacious; PCH-1 is termed comfortable; PGH-1, PGH-2, and PHM are described as compact, and the FHE-400 BRAS D'OR is touted for her volumetric efficiency.

Acceptable values for future hydrofoil ships will be predominantly functions of crew size and equipment maintainability and repairability requirements. The question of crew size in general, and the concern of providing the proper blend of habitability with minimum ship volume and weight constraints is shared by all advanced naval vehicle concepts. Access needs, and inherent volume requirements, for maintenance and repair of equipment is becoming better quantified as the hydrofoil concept matures and R & M data is collected. Work underway at the Boeing Company is assembling this data.

Thus far the discussion has dealt only with the gross vehicle parameter of total weight over total volume. As the twelve designs considered (in Figure 4) had wide variations in fuel load percentages, the data was corrected for fuel weight and volume, Figure 5. The corrected data shows good agreement between the means for the existing vehicles and the design studies; although there is considerable scatter for the existing hydrofoils, with all three USN combatants (PGH-1, PGH-2 and PHM) falling above the mean. The two R & D ships (PCH-1 and AGEH-1) suffer from the lack of an installed weapon system.

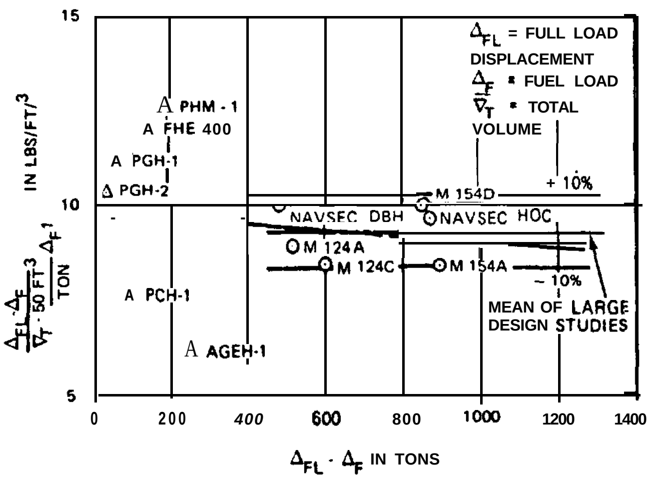


Fig. 5 Vehicle density based on full load displacement minus fuel load

Finally recognizing that the bulk of the lift systems were external to the hull, the data was again corrected. Figure 6, by subtracting lift system weights. A trend of increasing density with platform displacement can be identified.

Also identified in Figure 6 is the apparent existence of a "volumetric growth margin" inherently built into all design studies, which is perhaps a partial explanation of why vehicles can grow in weight during the successive design phases without significantly growing in volume. To quantify the potential upper limit of vehicle density, a new line was drawn, Figure 6, through the mean of the four most dense existing hydrofoils with a slope identified by the six recent design studies. A total vehicle density was then constructed by adding lift system weight from Figure 7 and fuel weight. (The mean trend line on Figure 7 did not include the three fixed lift system designs, FHE-400, M 154A, and M154D). Figure 8 resulted illustrating both potential total vehicle density and the effect of fuel load. The trends shown are considered valid for

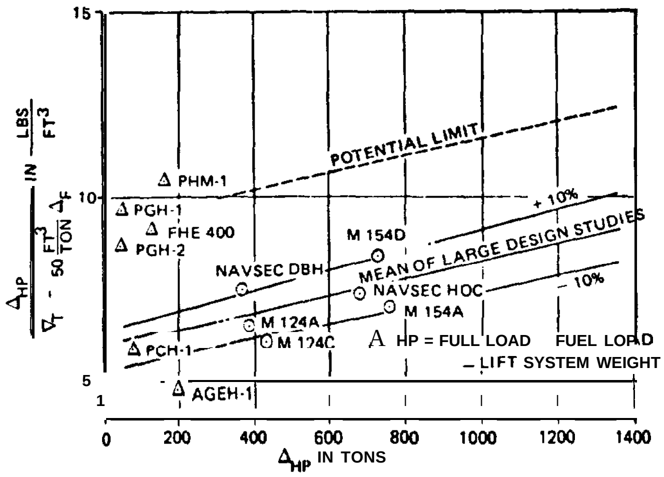


Fig. 6 Vehicle density - based on full load displacement minus fuel load and lift systems

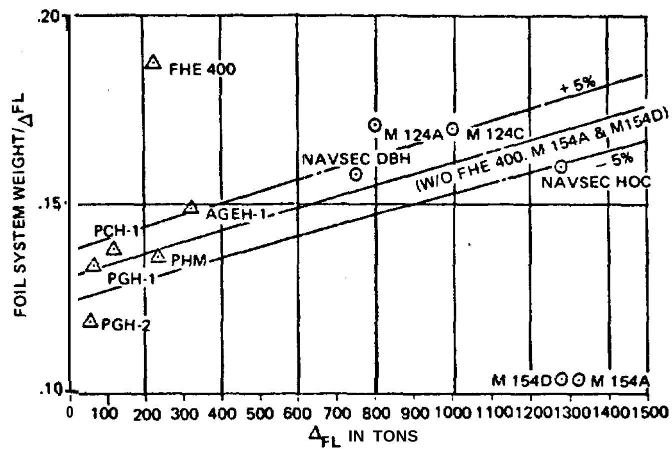


Fig 7 Distribution of foil system weight

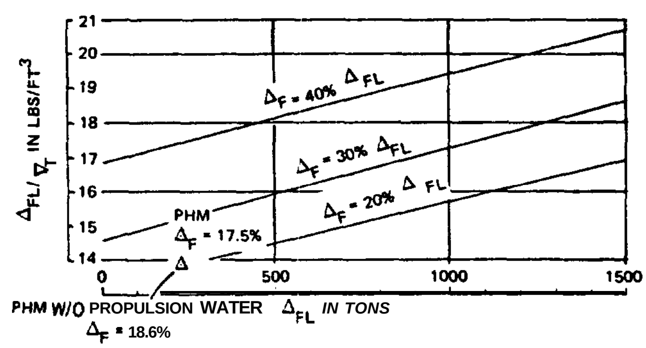


Fig. 6 Potential vehicle density - based on full load displacement

retractable-lift-system, propeller-driven craft. Non-retractable lift-system designs will have lower vehicle densities, as the bulk of the lift system is external to the containment volume, while waterjet powered craft will increase the vehicle density by a minor amount due to the relatively dense onboard propulsion water. PHM, with a fuel load of 17.5% of full load, as built, is shown as a reference. Correcting the PHM density for on-board propulsion water associated with the waterjets brings it into good agreement with the indicated potential trends.

While total vehicle volume trends can be identified by the preceeding, distribution between hull girder and superstructure volume is shown in Figure 9. There are pros and cons for designing to either side of the mean distribution shown. Small superstructure vehicles offer increased flexibility for weapon system arrangement, both in initial design and in future mid-life modification, but pay a penalty in structural weight as shown in Section VI following. In this regard Grumman designs M124A and C were developed to satisfy the Developmental Big Hydrofoil (DBH) * weapon system test bed requirement, and thus a design feature was to have the minimum superstructure to insure maximum armament location potential.

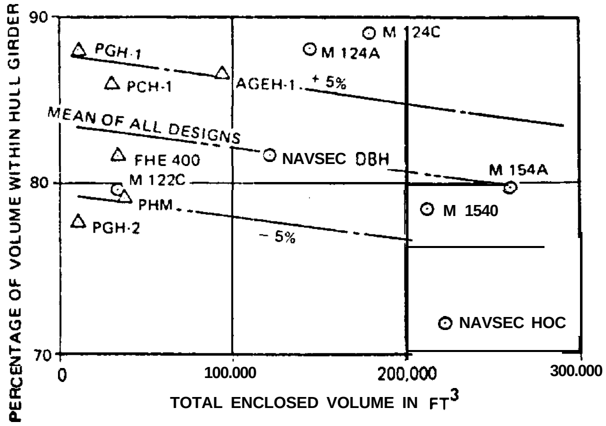


Fig. 9 Distribution of hull girder and superstructure volume

III. Hydrofoil Unique Design Features

Hydrofoil unique design features can be defined as those hull requirements which are necessary to the hydrofoil concept without regard to the mission of the total vehicle. These features are load distribution match between hullborne and foilborne conditions: hydrodynamic performance to insure take-off to foilborne; and when required the geometric interaction necessary for lift system retraction.

Load Distribution - Most discussions in regard to hydrofoil load distribution, center on the distribution of lift in foilborne mode between the forward and aft lift system arrays. The terms conventional, tandem, and canard are used to classify hydrofoil craft by lift system distribution. Figure 10, taken from (3) illustrated the generally accepted limits for each type. Existing hydrofoils have successfully utilized both conventional and

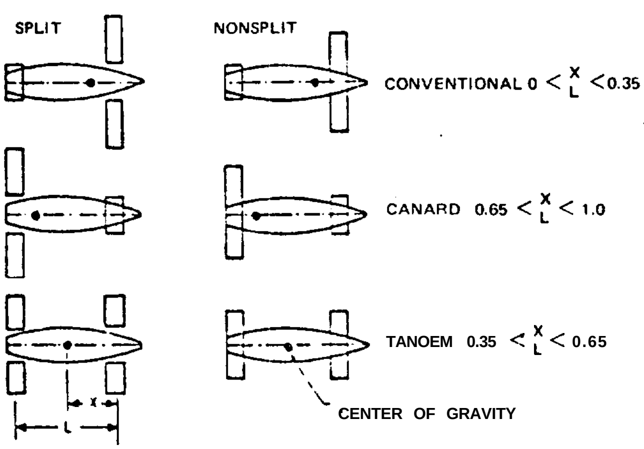


Fig. 10 Definition of foil area distribution

*In Navy Planning Stage CY72/73 Time Frame

canard configurations; the Grumman designed AGEH and PGH-1 being conventional, while the Navy designed PCH-1, the Boeing designed PGH-2 and PHM, and the Canadian FHE-400 being canard. Future larger hydrofoils with lesser strut length-to-ship length ratios and higher foil span-to-ship beam ratios will tend to employ tandem distributions. The final lift system distribution choice involves overall arrangement and weight distribution considerations including machinery and combat system element locations; retractability if required of the struts and foils; and foilborne hydrodynamic considerations relative to dynamic stability and control, maneuverability, and downwash effects of the forward foil on the aft foil.

Not often recognized however is the requirement of the hull form to match the selected vehicle load distribution with minimal changes in trim.

The single hull parameter which best defines the solution is the location of the longitudinal center of buoyancy (LCB) for the displacement of interest. Figure 11 illustrates historically typical values of LCB suitable for the various foil lift classifications defined in percentage of the hull length between perpendiculars (LBP).

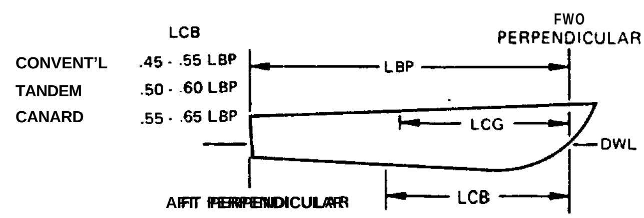


Fig. 11 Typical LCB locations for hydrofoil craft

For level trim hullborne the LCB location must match the location of the longitudinal center of gravity, LCG. It should be noted that on retractable system designs, lowering the foils will move the LCB and LCG for the total vehicle. For this reason hullborne level trim conditions cannot as a rule be precisely satisfied for both foils up and down, although experience has shown that limited excursions in trim can be attained under all conditions of loading and lift system position.

To present an illustration of the hull forms characteristics suited for each type of distribution the following figures taken from (1) are shown. The data in each figure has been normalized to a 1000 tons nominal hull displacement for comparison. The figures will also be utilized in the discussion of lift system retraction which follows. Figure 12 illustrates the AGEH hull form, with a conventional (90/10) distribution. To achieve the required LCB location a full sectioned hull was provided forward, with rather extreme tapering of the hull sections aft. Lowering the lift system elements (mains athwartships, and tail in the forward and aft plane) tended to move the total vehicle LCB and LCG forward to a match with the foilborne center of lift. Figures 13 and 14 illustrate two recent Grumman Aerospace Corporation designs for tandem lift system hulls. Design M124, Figure 13, has a 40/60 distribution; while Design M154, Figure 14, has a 50/50 distribution as illustrated, for which a retraction scheme can be developed at the expense of complicated mechanical arrangements. A 40/60 distribution is more practical. In both of these designs, having satisfied the distribution requirement, hull sections were chosen primarily for machinery arrangement, hullborne speed, and seakeeping requirements; resulting in rather fine lines forward with traditional sections aft. Due to the lift system distribution there is little excursion in LCG or LCB

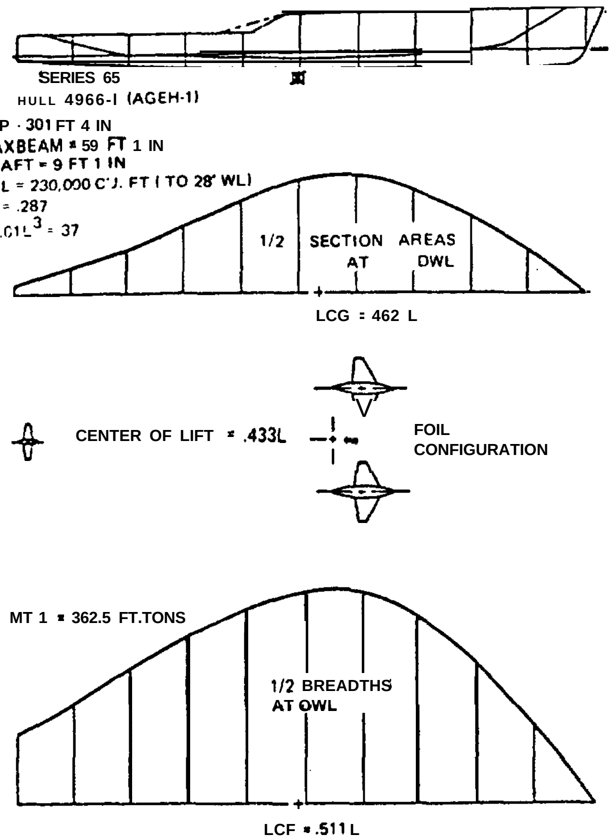


Fig. 12 AGEH-1 Hull form and conventional F/S configuration with 90/10 load distribution

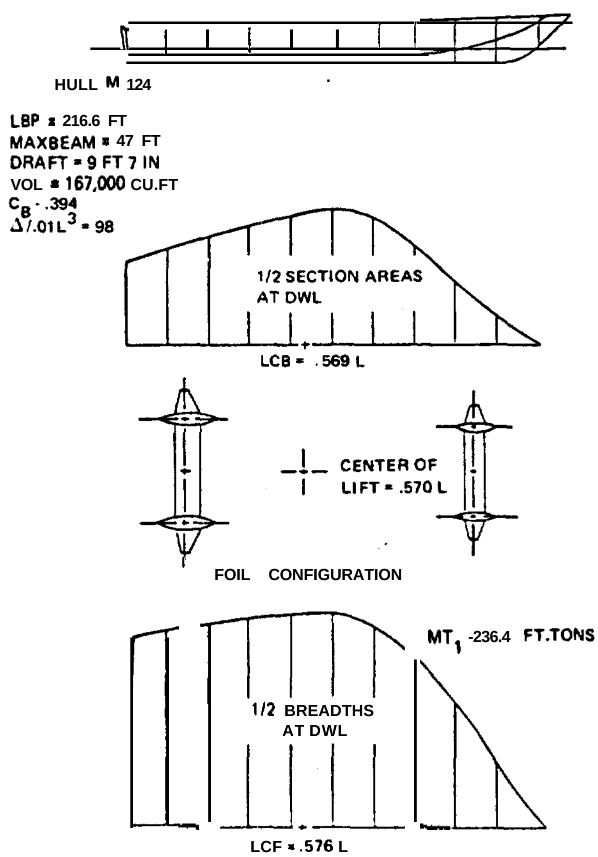


Fig. 13 GAC MI24 Hull form and tandem F/S configuration

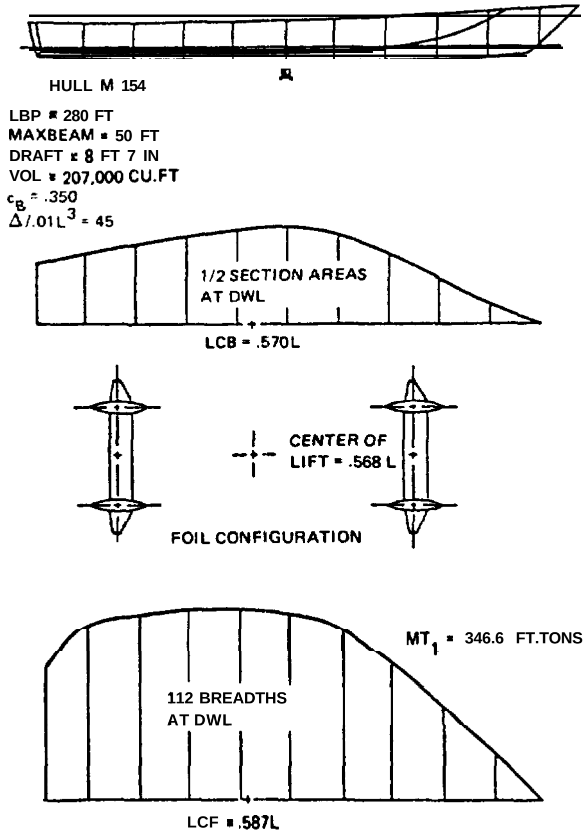


Fig. 14 GAC MI54 Hull form and tandem F/S configuration with 50/50 load distribution

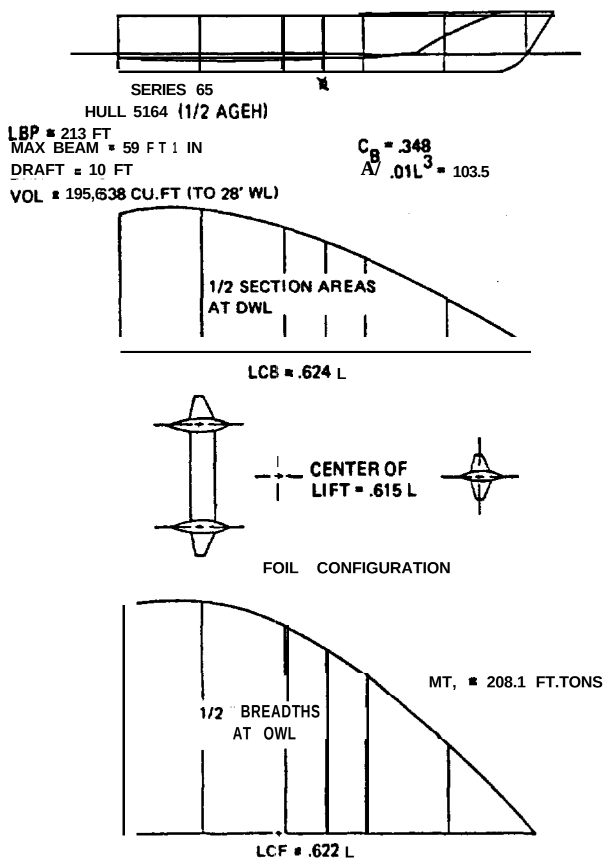


Fig. 15 AGEH-1 Derived hull form and canard F/S configuration with 30/70 load distribution

upon lowering of the foils. Final LCG and LCB values selected in the foils cxtcndcd condition were a function of second order hydrodynamic performance conditions. Finally we see in Figure 15, a canard foil system hull derived from the AGEH hull. The 30/70 lift system distributions results in a hull requirement for proportional fine section forward with extremely full sections aft. Lowering the lift system elements (both in the forward and aft plan) moves the total vehicle LCG and LCB forward.

Foil System Retraction

All USN hydrofoil ships have had retractable lift systems. AGEH and PGH-1 with conventional distributions, have split forward arrays which are retracted athwartships, and a single tail strut and foil pivoted over the transom in the fore and aft plane. All elements are lifted clear of the water for inspection and maintenance.

The lift system elements on PCH-1 are retracted vertically. This procedure, while reducing hullborne draft, does not facilitate lift system inspection and/or maintenance. The PGH-2 with a canard distribution has a mirror image of the PGH-1 retraction with split aft arrays retracted athwartships and the single forward array pivoted over the bow.

The PHM, with a canard distribution, has a single foil aft supported by two struts which retract over the stern; and a single forward strut and foil which swings over the bow.

Generally each of these retraction schemes have imposed no severe requirement on the hull arrangements.

The reason is explained by reference to Figure 10. The parameter X is defined as the distance from the craft LCG to the forward foil array, and the parameter L is the distance between arrays. Both parameters can be varied in proportion maintaining the same distribution. With athwartship retraction of either the forward or aft elements (AGEH, PGH-1, and PCH-2); the location of the other array can be located for convenience in establishing the retraction geometry and mechanisms, and the longitudinal location of the athwartship retracted elements adjusted by varying "X" with "L."

In establishing the retraction geometry for the PHM, the location of the critical single forward strut and foil was developed, and the location of the aft array was determined by again varying "X" and "L." This procedure resulted in the aft array passing the stern with greater than needed, although acceptable, clearance.

Experience with all retraction methods today have been favorable with the following minor notations. Retracting the main elements athwartships (AGEH, PGH-1, PGH-2) have imposed additional requirements on static stability which have been met. Pivoting a single forward strut and foil (PGH-2 and PHM) necessitates a bow closure door which was a source for several failures on PGH-2. An improved bow door design was developed for PHM based on the PGH-2 experience.

Retraction arrangement for future larger hydrofoil ships will not bc as readily achieveable as on past designs. The reasons are several, but most are related to achieving higher hydrodynamic performance in both foilborne and hullborne modes. For a given foil loading, foil dimensions increase by the 2/3 power of displacement, while hull dimensions increase by the 1/3 power. Foil cfficiencg is increased with incrcnscs in aspect ratio of the planform. Thus as future vehicle size increases, both foil dimensions relative to hull dimensions and aspect ratio will increase eliminating the possibility of split foil arrays or single strut and foil combinations as found on the AGEH-1, Figure 12. Athwartship retraction will not bc possible without a center line break joint on the foil. With larger relative foil spans, minimum operational beam will be achieved with near tandem distributions. The most practical rctrnction geometry is to retract the forward array over the bow and the aft array over the stern, with the shortest hull (relative to strut length) with an LCB closest to amidships offering the easiest solutions.

Better hullborne performance however is achieved with longer hulls, while good seakeeping ability results in LCB locations about 7% of the hull length aft of amidships. With these additional requirements the lift system distribution will favor the aft array. Thus the total mission requirement of the vehicle has an influence on lift system distribution by reason of practical retraction arrangements.

Hull length has in influence on trim excursions between foilborne and hullborne modes. The measuring parameter is MT1 or the moment required to trim the craft one inch hullbome. Typical MT1 values are shown on Figures 12 to 15, and illustrate that resistance to trimming is primarily linear with hull length. Thus the designer has a slightly easier task balancing foilborne and hullbome trims with the longer craft.

Take-Off Hydrodynamic F'erformance

Historically the analysis of the hydrodynamic performance of hulls during the take-off transition was initially based on seaplane technology, as reflected in early hydrofoil hullform selections. As the hydrofoil technology matured, it was recognized that the dynamic attitude of the seaplane (thrust over drag vectors producing a bow down trim) and higher take-off speeds of the aircraft were not appropriate to the hydrofoil conditions. Thus hydrofoil designers turned to planing craft technology for both design data and analysis techniques. Although hydrofoil hull design is presently considered by some to be a branch of planing craft naval architecture: it is more precisely defined as a separate, but similar field of technology. The hydrofoil hull in take-off differs from the planing hull in that being constantly unloaded it has no fixed design displacement; is subjected to high hull trimming monents from the position of drag vector from the lift system and thrust vectors on propeller-driven craft; rarely if ever, achieve a positive attack angle of the aft underbody (necessary for the definition of planing); and in general experiences maximum drag values at forward velocities other than those experienced in planing craft. Planing craft literature however serves as a valuable source of initial design data, and suggestions for improvement of analysis techniques. A recent typical paper (4) contains analysis techniques (and excellent propeller data) which may have application to hydrofoil technology, although the planing craft illustrations arc not directly applicable.

To illustrate the relative contribution of the hull to the total hydrofoil drag during the take-off transition some typical cases will be shown based upon actual hull model test data found in (5). This reference describes the design M122 hull configuration chosen and subsequently model tested in 1971 by Grumman Aerospace Corporation in anticipation of a design competition for the Navy's PHM program. Although the program was awarded without competition, the Boeing Company hull configuration was subsequently modified after contract award to be nearly identical with the M122 hull form. The extensive towing tank tests completed by Grumman, (6), provides an adequate data base for valid prediction of hull drag and pitch for a considerable range of design displacements and loading conditions. "Design"* displacement of M122 was 172.8 tons with a hull length (LBP) of 120 Ft. yielding a displacement-length ratio $\Delta/(.01L)^3$ of 100. Anticipated take-off speed was 25 knots.

Where Δ is the hull displacement - tons
L is hull length -Ft.

Typical residual resistance coefficients $C_R (= R_R/\frac{1}{2}\rho V_o^2 S)$ for M122 are shown in Figure 16.

Where R_R is Residual resistance - lbs.
ρ is Water density - lb-sec^2/Ft^4
v is Velocity - Ft/sec
S is Wetted area - Ft2

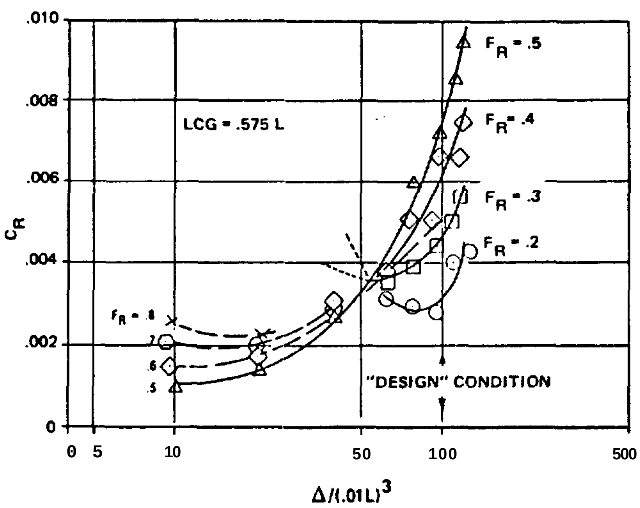


Fig. 16 Typical residuary resistance coefficients for M122

This data is expanded and added to frictional drag for two illustrative hull sizes of 100 and 1065 tons, Figures 17 and 18, both for 25-knot take-off conditions. Note that maximum hull drag occurs at similar forward velocity but at dissimilar froude numbers $(F_R = V_0/(gL)^{1/2})$.

Where V_0 is Velocity - Ft/sec
g is Gravity 32.2 Ft/sec^2
L is Ship length - Ft

Planing craft theory would predict maximum hull drag at a constant froude numbers (between .4 and .5) independent of vehicle displacement. For the larger craft (1065 Tons) a higher take-off speed of 35 knots was considered, Figure 19. A standard unloading with hull displacement inversely proportional to take-off speed squared $(\Delta_H = \Delta_D(1 - V_k/V_{T.O})^2)$ was used in this analysis.

Δ_H is instantaneous hull displacement - tons
Δ_D is Design displacement - tons
V_k is Speed-knots
$V_{T.O.}$ is Take-off speed-knots

Figure 20 compares the hull resistance per ton, and corresponding "lift" to drag ratios for the three examples. At 25-knot take-off conditions, the relative hull resistance of the smaller craft (100 Tons) is about twice the resistance of the larger (1065 Ton) craft. Compar-

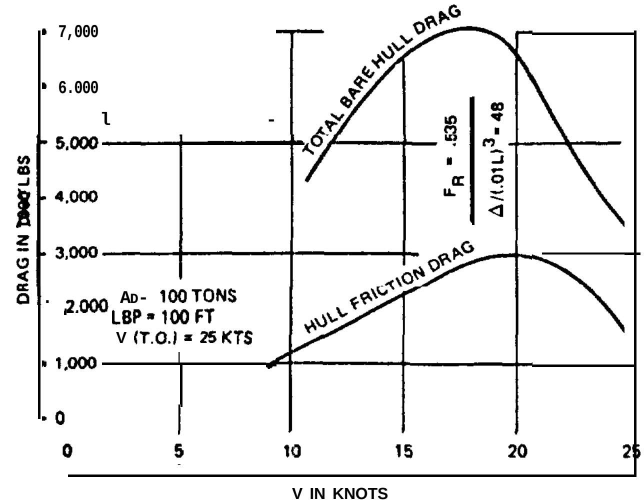


fig. 17 M122 Bare hull drag for 100-ton, 25-knot takeoff speed design

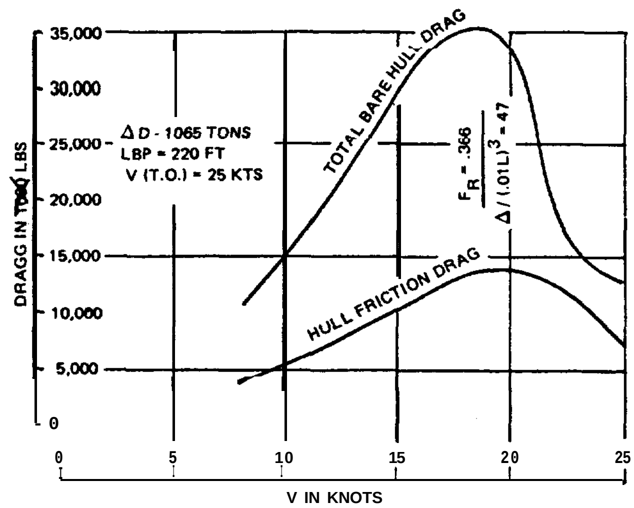


Fig. 18 M122 Bare hull drag for 1065-ton, 25knot takeoff speed design

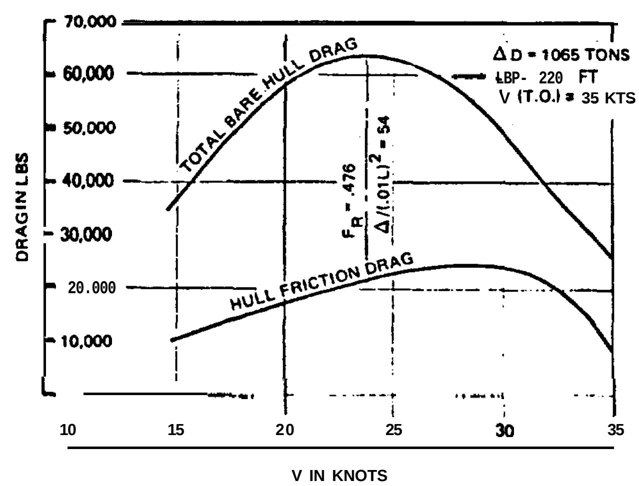


Fig. 19 M122 Bare hull drag for 1065-ton, 35-knot takeoff sped design

ing take-off speed conditions, for the same displacement hull resistance is similar up until about 23 knots, where hull "L/D" (-20) is greater than to be expected *from* the foil lift system at this speed. This illustrates that as hydrofoils grow in size and length increasing take-off speed has certain advantages, primarily if it is desirable *to* optimize the lift system hydrodynamic design for max-

*Hull "Design" Displacement by Grumman standard practice for hull development is full load displacement minus one-half fuel load.

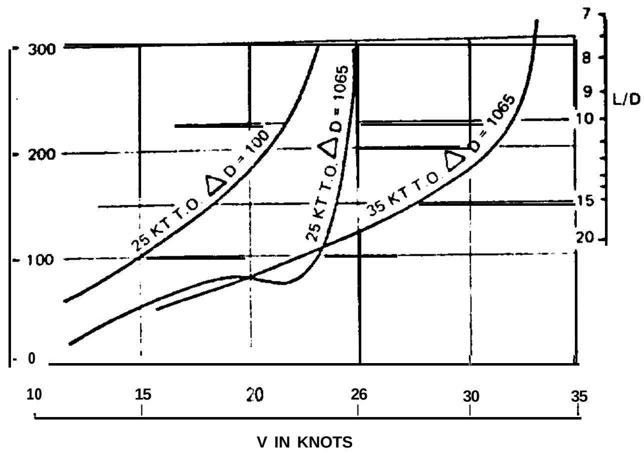


Fig. 20 MI22 Bare hull resistance per unit displacement and L/D

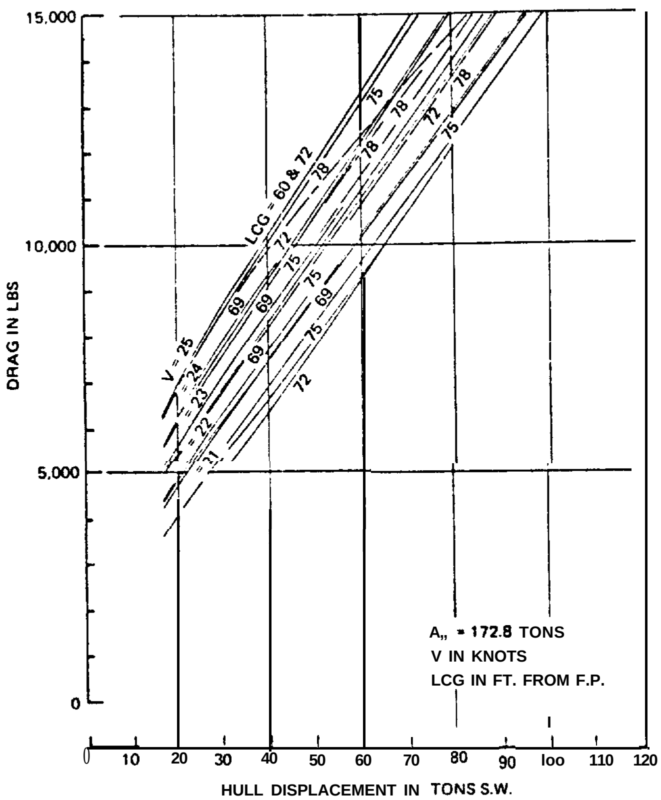


Fig 21 MI22 Hull takeoff drag speed and LCG vs Δ

imum foilborne speeds. Foil efficiency at take-off speed can be compromised to achieve better maximum speed efficiency, and the transfer of lift from the hull to the lift system delayed in compensation. This can be accomplished because hull "L/D" ratios are a function of froude speed relationship, while foil system "L/D" ratios are a function of absolute velocity. Indeed, early historic concerns about getting "over the hump" at take-off are diminishing with increasing vehicle size. The "worst" combination of hydrofoil size and take-off speeds have probably been presented in the existing PHM design, where the lowest foil and hull efficiencies were coincidental for 25 knot take-off conditions. While adequate thrust could be provided with propellers at these conditions, a satisfactory solution was achieved with the PHM waterjets by increasing take-off speed; in effect allowing the hull to operate more efficiently before transfer lift to the foils

Note on Figures 17 through 19 the hull drag value identified at take-off zero hull displacement. This drag component is caused by spray and water adhesion with the keel transiting from the still water surface. While this phenomenon had been suspected previously, it was positively identified for the first time in (6), and has been verified in subsequent model tests conducted by Grumman Aerospace Corporation.

Of final discussion is the effect of dynamic trim during take-off. Because the hull can be subjected to wide variations in trimming moments due to the drag of lift system components (causing bow down trim), different ial lift from the forward and aft foils, and acceleration thrust excursions (causing bow up trim on propeller driven craft) it is desirable to provide hulls which are relatively insensitive in trim and drag variation to these effects. Analytically the trimming moments are treated as hull static moments providing a shift in the craft longitudinal center of gravity (LCG). Figure 21 illustrates the achievement of this objective for a previously discussed typical hydrofoil hull. Corresponding trim excursions were on the order of one degree maximum.

IV. Hydrofoil Mission Related Features

Mission related features are defined as those hull requirements dictated by the mission of the total design. Included within these features are:

- Hullborne Speed
- Hullborne Seakeeping
- Weapon System Arrangement
- Stability
- Subdivision
- Fuel Tankage
- Retraction Necessity
- Foilborne Maneuvering
- Hullborne Maneuvering

While none of these features are necessary to the hydrofoil concept, each contributes to the military worth of the hydrofoil, and in some measure, effects the solution of hydrofoil unique features discussed in the preceeding section.

Hullborne Speed

Historically hullborne speeds of hydrofoils have received minor consideration. What could be achieved without difficulty was accepted with little question. Hullborne speed (and range) ability were sacrificed to achieve the best foilborne performance resulting in effective vehicle speed gaps of as high as 25 knots between maximum pure hullborne speeds and minimum continuous foilborne speeds.

Unfortunately the demonstrated hullborne speed abilities of hydrofoils have a tendency to be incorporated into the mission effectiveness studies addressing future hydrofoil requirements, short-changing the concept.

Future larger hydrofoil ships can be designed to achieve high hullborne speeds at fuel economies not unlike conventional hull as shown in (1). Figure 22 compares the bare hull resistance of the four representative hydrofoil hulls discussed in the preceeding section. All results are based on hull model tests.

While increases in hullborne speed are achieved with high length-to-beam ratios, adequate transverse stability can be maintained; and as will be shown later in this paper, without increase in hull weight.

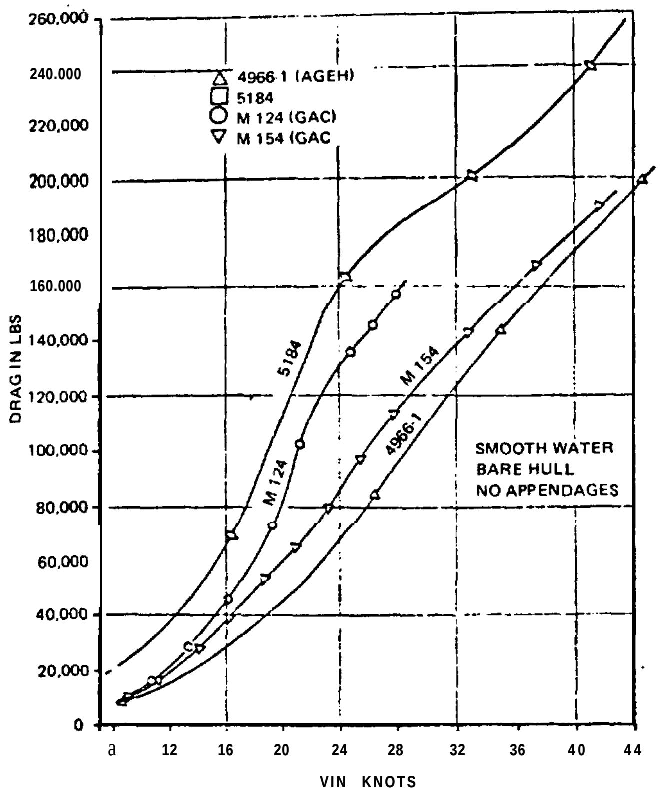


Fig. 22 Comparison of hull drag at Δ = 1000 tons

With proper design attention mission effective speeds over the entire velocity profile from zero to maximum foilborne speeds can be achieved.

Hullborne Seakeeping

With increasing attention to higher hullborne speeds, greater emphasis will be placed on seakeeping at these speeds. Good seakeeping is achieved with higher length-to-beam ratios, fine entrance bow section, sufficient freeboard, and attention to longitudinal weight distribution. With decreasing emphasis on take-off drag as discussed in the preceeding section, these features can be designed into future hydrofoil hulls.

Recent seakeeping tests, (7), demonstrated the potential ability of a nominal 1000 Ton hydrofoil hull to achieve speeds of 25 knots in sea state 6 without slamming and propeller unwetting.

Yet to be fully documented is the effects of foil damping on hull motions with the foils extended at high hullborne speeds. Canadian studies indicate that, due to the motion damping effect of the foil system, the hullborne drag in sea states can be less with the foils down than with the foils retracted.

Weapon System Arrangement

Dictates of good weapon system favor maximum weather deck space and minimal superstructure, tending to increase hull structural weight. Radar and radio frequency antennas favor high installation locations, adversely effecting transfer stability in wind. Counter to this is the increase in antenna height during foilborne operation.

Missile blast-effect concerns and armament reload and magazine locations relative to armament arrangements arc not unlike conventional military platforms,

In the deployment of linear and towed sonar systems from hydrofoils during hullborne operations the motion stabilization characteristics of the craft with the foils extended offer certain advantages over conventional ships. Normal deployment of sensors over the stern in future hydrofoils will be with the aft foils and struts extended to preclude interference with the retracted lift system elements. This arrangement will allow rapid transition from hullborne to foilborne while towing.

Elimination of vertical and flat side plating on future ships to minimize radar cross section will be as required on conventional ships.

Stability and Subdivision

Implicit to the discussion of these subjects is the recognition that hydrofoil craft are in essence conventional naval craft with large topside wrights and sail area conditioned by the retraction of the lift systems. With foils extended, hydrofoil craft have more than adequate stability to withstand high wind and wave conditions; in most instances far greater than ships of similar size and mission. Stability in the foils extended condition is most often in excess of that required in the design sea environment for the craft. Retraction of the lift system for whatever purpose; for military mission reason such as higher hullborne speed, or while at anchorage raises the vehicle center of gravity and increases the lateral wind area. This condition governs the ability of the craft to satisfy the stability and buoyancy criteria.

Criteria

The stability and buoyancy criteria generally applied to hydrofoil craft can be found in (8), and more recently in (9). Of note is that while (9) specifically addresses "Advanced Marine Vehicles" the criteria contained therein for hydrofoil craft types in unchanged from the criteria of (8); which has been successfully applied to hydrofoils for more than a decade by competent naval architects. All other craft types treated in (9) required a redefinition of criteria for their non-conventional hull forms.

Also of interest, neither references are presently classified as specifications for U.S. Navy ships.

In summary the governing stability and buoyancy criteria for hydrofoil (and convention) ships is as follows:

Intact Stability. Be able to sustain a wind velocity of from 60 to 100 knots depending on craft size and mission without adverse roll (no greater than 15" max.) and with sufficient reserve restoring energy to withstand wind accompanied waves.

General application to hydrofoils to date has been to specify a 80 knot wind.

A second intact stability criteria addresses roll moments caused by lifting of large weights and side crowding of passengers. These have not had application to hydrofoil craft.

High Speed Turning. Be able to turn at high speed (hullborne) with a heel angle of no more than 10° for new designs with adequate reserve restoring energy to prevent capsizing under the action of wind and waves.

Previously not applied to hydrofoils due to relatively low hullborne speeds. May have application to future designs with higher hullborne speeds.

Top Side Icing. Be able to sustain an ice accumulation of 3" or 6" (thickness specified by design requirements) on all exposed horizontal and vertical surfaces in a specified beam wind without adverse roll with sufficient reserve restoring energy to withstand wind accompanied waves.

Previously not applied to hydrofoils due to anticipated areas of operation. May be applied to "blue (white) water" designs, with potential application of unsymmetric icing conditions.

Damaged Flooding.
a) For craft less than 100 Ft. in length, be able to withstand the flooding of any single main compartment.
b) For craft between 100 and 300 Ft. in length, be able to withstand the flooding of any two adjacent compartments.

Damaged Stability. Be able to have adequate stability under flooded conditions (preceeding) with no more than 15° of heel with adequate reserve restoring energy to sustain rolling from moderate seas.

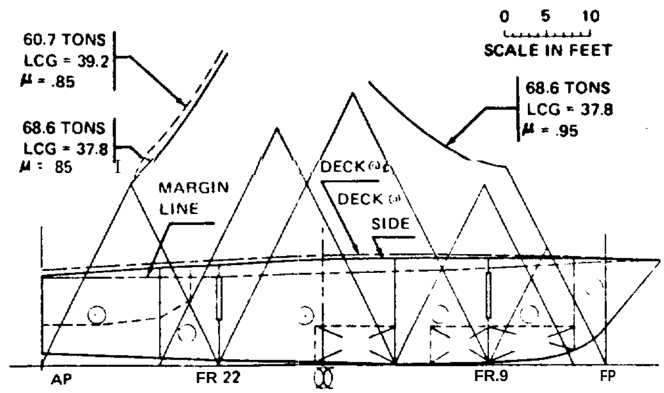
Performance of Existing Designs

All existing hydrofoil craft have met the stability and buoyancy criteria as summarized in Table I.

In general the criteria has been applied and evaluated at two operating conditions, full load and minimum operating. The latter condition assumes one-third fuel load and reduced amounts of other disposable loads. For hydrofoil craft, as in most other naval ships, the minimum operating condition establishes the governing situation. Studies now being conducted at Grumman Aerospace Corporation in assessment of criteria for future hydrofoils are addressing the reality of a minimum operating condition with near zero fuel.

In application of the criteria to existing hydrofoils, the most difficult solutions have been those designs with main machinery aft. In the minimum operating condition these craft as a rule trim bow uptending to decrease the ability of the craft to sustain flooding aft. Prudent design practice has dictated that floodability analysis be conducted over the crafts operating range of expected trims. Figure 23 illustrates this analysis for PGH-1 FLAGSTAFF.

The criteria for Damaged Flooding (preceeding) does not specify a minimum damage length for U.S. Navy ships under 300 Feet in length. Recognizing that the criteria could be impractically satisfied by numerous



NOTE: MAIN PROPULSION TURBINE ℄ COMP'T. & FUEL TKS' CONSIDERED DAMAGED WITH COMP'T

Fig. 23 PGH-1 Flagstaff floodable lengths two-compartment subdivision

closely spaced water-tight bulkheads, Grumman Aerospace has recommended and applied as a design standard a minimum effective bulkhead spacing of 5 Feet +3% (LBP in feet). For FLAGSTAFF (Figure 1) this resulted in a minimum bulkhead spacing of 7 Feet.

An additional recommended practice has been to assume that adjacent foil foundation support bulkheads will both be rendered non-watertight in the event of a hard grounding foilborne. General practice has been to assume that integral fuel tanks are flooded in measuring subdivision while remaining undamaged in assessment of damaged stability.

Performance of Future Designs

Future hydrofoil craft, particularly larger ships, in view of past experience should have little difficulty in providing adequate intact and damaged stability. Principally because future craft will tend to have 90° foil retraction arcs as opposed to near 180° arcs on several of the existing hydrofoil vehicles. In addition while lift system weight percentages (of full load) will tend to increase with displacement, strut lengths will tend to decrease in proportion to size, (10). Vehicle vertical center of gravities will tend to a constant value (without fuel) as a function of the number of decks contained within the hull: as illustrated in Figure 24. Thus while the overall effect will be a proportional rise in vehicle center of gravity with retraction (essentially a function of foil system weight percentage), sufficient stability can be maintained with 90° retraction arcs.

Table I. Intact and Damaged Stability Criteria of Existing Hydrofoil Craft

Craft	Compartments	Minimum Compartment Length (in feet)	Number Floodable	Stability Criteria
PCH-1	6	10	1	Criteria not specified. (Vertical Foil Retraction)
AGEH-1	11	12	2	80 Knot Beam Wind Intact
PGH-1	6	7	2	SO Knot Beam Wind Intact
PGH-2	5	8	1	80 Knot Beam Wind Intact
PHM-1	8	10	2	80 Knot Beam Wind Foils Extended 50 Knot Beam Wind Foils Retracted Both Intact

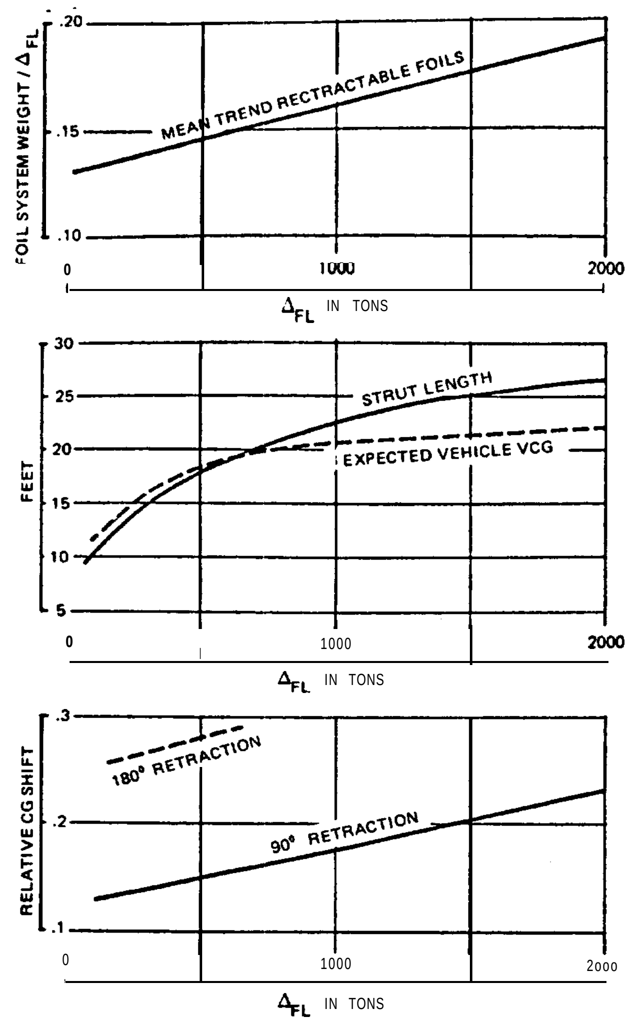


Fig. 24 CG, **strut length,** and **strut** foil system trends with retraction **vs** ship **displacement**

In addition the effect of greater disposable loads (principally fuel) on future designs tending to cause a wider range in vertical center-of-gravity shift from full load to minimum operating conditions must be considered.

Future hydrofoils will also tend to have greater length-to-beam ratios reducing the initial of heel. Initial stability up to approximately **15°** of heel can be stated in the form of:

$$\left[\overline{KB} + \frac{C_I\, LB^3}{\nabla} - \overline{KG} \right]$$

Where: $\overline{KB}$ is the vertical center of buoyance -Ft.
$\overline{KG}$ is the vertical center of gravity. - Ft.
L is the ship water line length -Ft.
B is the maximum beam at the waterline - Ft.
V is the volumetric displacement - Ft.^{3}
and CI is a coefficient based on water plane form.

If we assume a 100 Ton displacement craft has a length of 100 Feet and a beam of 20 Feet, initial satbility will be:

$$\left[\overline{KB}_{100} + C_I\,(395) \right] - \overline{KG}_{100}$$

If this hull is expanded to 1000 Ton displacement without change in form and retaining the L/B ratio of 5, initial stability will be:

$$\left[2.15\ \overline{KB}_{100} + 2.15\, C_I\,(395) \right] - \overline{KG}_{1000}$$

However expanding the 100 Ton hull to 1000 Tons retaining the same form but increasing the L/B ratio to 6 initial satbility can be shown to be:

$$\left[2.02\,\overline{KB}_{100} + 1.17\, C_I\,(395) \right] - \overline{KG}_{1000}$$

Thus initial stability is potentially lowered by increasing L/B. However vehicle vertical centers of gravity as shown in Figure 2-l are expected to tend to a constant value.

Figure 25 illustrates the overall expected trend.

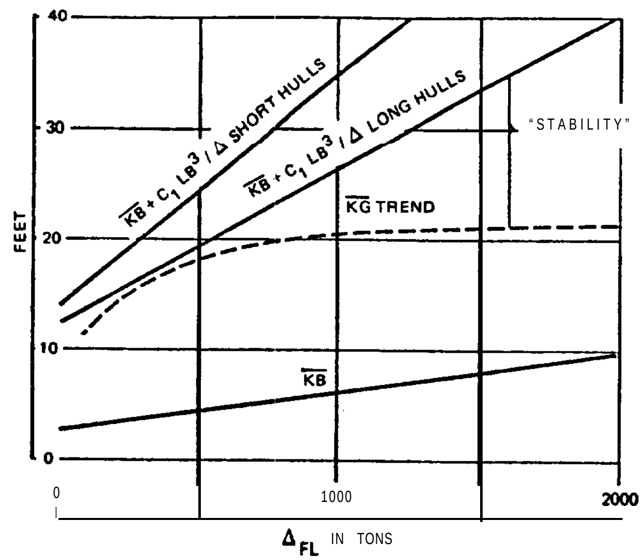


Fig. 25 $\overline{KB}$, $\overline{KG}$, Stability trends

Design studies conducted at Grumman Aerospace on hydrofoil **ships** up to 1660 Tons have verified the ability to provide adequate stability to that displacement, (see Figure 26), for the minimum operating conditions.

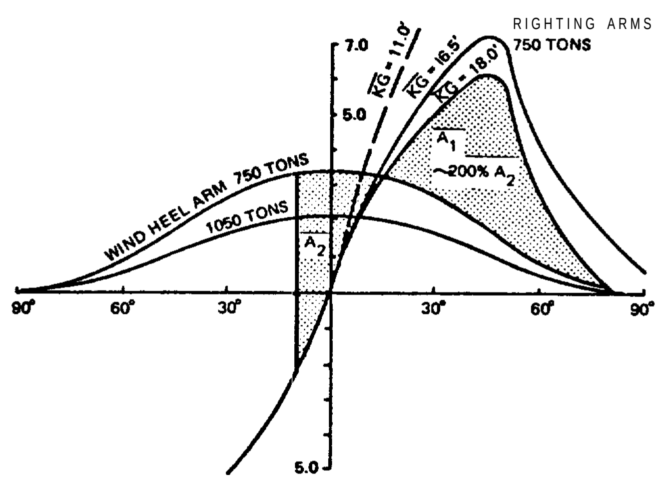


Fig. 26 Design M154A. Intact stability, 100-knot beam wind

Hazards Unique to the Concept

Historical hazards unique to the hydrofoil concept have fallen into three types; log'strikes, whale encounters, and hard grounding foilborne.

The frequency of occurcnce of the first two have been primarily a function of the operational areas chosen for hydrofoils on the West Coast of the United States in the

Pudget Sound and Southern California regions. Both basically occur at high vehicle speeds, and have not endangered the watertight integrity of the hull.

Hard grounding hazards are a function of both high vehicle speed and navigational ability. The damage incurred to the PGH-2, the only hydrofoil craft stricken from the Navy inventory, would in all probability have been as severe if a planing or displacement craft had addressed the same reef at similar speed. Continued attention however should be maintained in future designs to take into account this potential hazard.

Fuel Tankage

Increasing fuel percentages (of full load) of hydrofoils introduces the necessity of both providing sufficient tankage and the control of fuel utilization to maintain acceptable foilborne and to a lesser extent hullborne longitudinal distribution. General this can bc achieved by providing fuel tanks in a quantity defined by the following empirical relationship:

No. of Fuel Tanks* = (22→28) (Fuel Load/Full Load)

Number and location of the tanks have a second order effect on damaged stability.

The increasing percentages of fuel on increasingly larger hydrofoils has a pronounced effect on intact stability. With hard chine hulls a very "stiff" condition can result at one displacement with a rapid fall-off in stability as fuel is consumed. For this reason, among others, future designs will tend to have generous bilge radii to provide uniform "stiffness" over the operating range of displacements.

Retraction Iiecessity

The preceeding section, described the hydrofoil unique requirement and ability to retract the lift system. The necessity of such retraction is a mission consideration. There are many pros and cons to the issue of retraction necessity which will not be answered here.

The retraction of the lift system reduces the operational draft of the vehicle, reduces channel requirements, but not the operational beam of the ship. Marine growth on non-operating foils is reduced, Lift system maintenance and drydocking are easier with retraction.

The penalties for retraction are: potentially more complex machinery arrangements, greater lift system hull system integration concerns, and greater lift system weights. Retraction time has minor significance in the assessment of these penalties.

Fixing the lift system also introduces the possibilities of reducing strut length and allowing the keel of the hull to knife through the higher waves in the design sea state. Combined with 50/50 tandem distribution this potential arrangement would offer the lowest draft and submerged beam combination. Hull length would not be restricted by any static considerations.

Foilborne and Hullborne Maneuvering

The overall hull length and vehicle distribution effects strut location and maximum foil span. For foilborne flat turn maneuvers the strut location, and forward and aft strut spacing, describe the effective length of the vehicle. As flat turn diameters are described in effective ship lengths (the forward and aft spacing of the struts) increasing ship length increases the turning diameter. Thus increasing hull length with retractable foil systems tends to increase foilborne turning diameters for the flat turn condition.

In the foilborne coordinated turn maneuver condition, maximum foil span together with foil submergence define the maximum allowable roll angle. Typically a 90 Ft. span foil at 12-1/2 Ft. submergence rolling 12-1/2° would bring the foil tip to within 30 inches of the water surface without increase in submergence. At forty-five knots under these conditions, the turn rate would be limited to 5-1/2°/sec and the corresponding turning radius would be 800 Ft. "Digging in" on a coordinated turn, along with other options now under study can reduce the practical turning diameters.

The military effectiveness of high speed, high maneuverability of the hydrofoil concept over conventional and other "advanced" concepts only now is being fully understood and appreciated.

The hullborne maneuvering hydrodynamic characteristics of the hydrofoil are no different than conventional hullforms of similar proportions. Historically, however, all as a class are somewhat unusual in that all have used some method of active thrust vectoring to effect control. The DENISON and FLAGSTAFF used steerable nozzles on the hullborne waterjets, and could turn at zero forward speed. PLAINVIEW and HIGHPOINT use steerable outdrive units. The designs of the TUCUMCARI and PEGASUS used bow thrusters.

Future designs with increasing emphasis on higher hull speeds and decreasing concern about appendage resistance during take-off will tend toward more conventional hullborne steering systems.

V. Hullborne Propulsion

The hullborne propulsion system characteristics of previous and esisting U.S. Navy hydrofoils are summaried in Table II. Generally they share certain common features. All, in keeping with the emphasis on foilborne performance, where considered secondary in importance to the foilborne propulsion plant; resulting in most instances in less than optimum performance. Primary emphasis has been on providing low speed maneuvering and low-to-mid endurance for long range ferrying of the ships.

Of interest is that, with the exception of the H.S. DENISON, all have had diesel driven hullborne propulsion systems. The major reason has probably been the inherently economical fuel rates of diesels as compared with gas turbines in the horsepower sizes required. A more subtle reason may have been a desire to provide the most reliable "back-up" propulsion system possible. This supposition is reinforced by the fact that all hydrofoils to dntc have had completely separate foilborne and hullborne propulsion systems. The hydrofoil community was probably the major early driving force in the marinization of the gas turbine for naval use, and as with all new applications the resulting product had sonic question in regard to reliability.

Note too, that all hullborne propulsors have in some fashion been selected to provide minimum added resistance on take-off of the hydrofoil.

With increasing hydrofoil ship size, decreasing sensitivity to take-off resistance, emerging mission requirements for higher hullborne speeds, and resulting larger

*Port and starboard pairs arc considered to be one tank. For port, centerline and starboard tanks the multiplier is reduced to 15→21

Table II. Hullbornc Propulsion Systems U. S. Navy Hydrofoils

	Denison*	PCH-1 Highpoint	AGEH-1 Plainview	PGH-1 Flagstaff	PGH-2 Tucumcari	PHM-1 Pegasus
Prime Mover	Gas Turbine (1) GE-T-58	Diesel (1) DD-12V-71T	Diesels (2) DD-12V-71T	Diesels (2) DD-6V-53N	Diesel (1) DD-6V-53N	Diesels (2) MTU 8V 331 TC80
Rating (Cont.)	795 BHP @ 19,500 RPM	540 SHP @ 2,100 RPM	500 BHP @ 2,100 RPM (Each)	160 BHP @ 2,600 RPM (Each)	160 BHP @ 2,600 RPM	661 BHP @ 2,200 RPM (Each)
Propulsor	Water Jets (2)	Propeller (1)	Propellers (2)	Water Jets (2)	Water Jet (1)	Water Jets (2)
Description	Beuhler 12" Dia. 3 Stage Axial Flow 2,250 RPM	3 Bladed 43" Dia. Sub Cavitating, F.P. 800 RPM	5 Bladed 48" Dia. Sub Cavitating, F.P. 525 RPM	Beuhler 165-1-C 16.5" Dia. Single Stage Axial Flow (Transom Mt.)	Beuhler 165-1-B 15.7" Dia. Single Stage Axial Flow (Transom Mt.)	Aerojet AJW 800-1 26.4" Dia. Single Stage Axial Flow (Transom Mt.)
Retractable	(Flush)	Yes	Yes			
Steering	Steerable Nozzle Reversing Bucket	Steerable (360°) Outdrive	Steerable (360°) Outdrive	Steerable Nozzles Plus Differential Thrust Reversing Buckets	Steerable Nozzle Plus Bow Thruster Reversing Bucket	Steerable Nozzles Plus Bow Thruster Reversing Buckets

*Transferred to C.S. Navy at Pacific Missile Range

installed hullborne horsepower; significant changes will be made in hullborne propulsion machinery. Figure 27 illustrates some of the possibilities. All gas-turbine plants; particularly for larger ships, will probably be the accepted practice. The continued need for totally separate foilborne and hullborne propulsion systems is under question, particularly when the hullborne power requirement may equal or exceed 50% of the foilborne power needs. If the foil systems are non-retractable or maintenance retractable only, is there a need for a distinction between hullborne and foilborne machinery? Finally if a single machinery plant is used for both hullborne and foilborne operations, can the most economical fuel rates be achieved with Combination Gas Turbine or Gas Turbine (COGOG) or Combination Gas Turbine and Gas Turbine (COGAG) systems using a mix of gas turbine sizes?

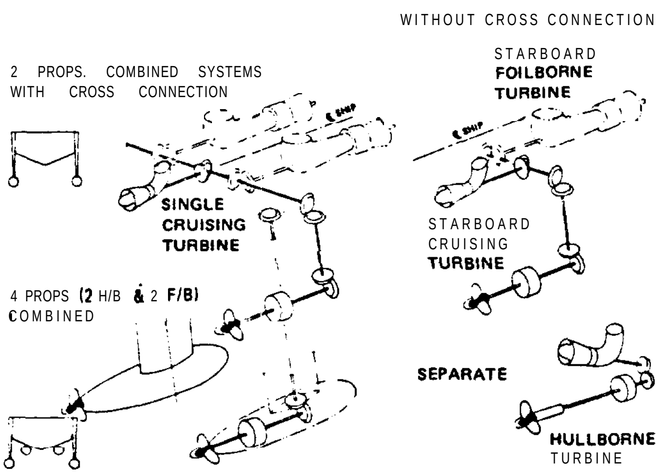


Fig. 27 Future hullborne propulsion options

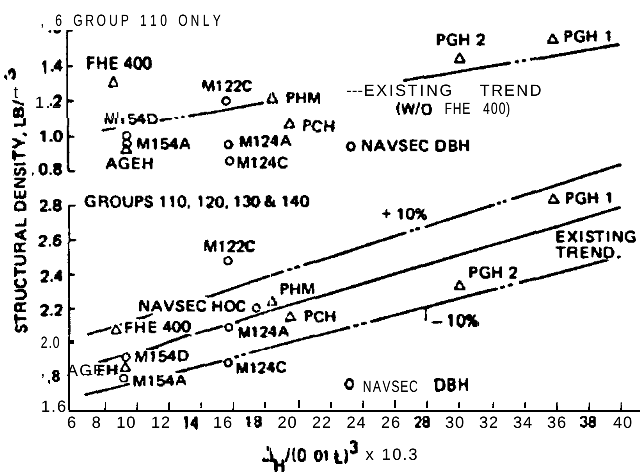
VI. Structural Considerations

Hull loading criteria in impact and overall bending has been the subject of considerable study in the past and undoubtedly will continue to be for the foreseeable future. Work now underway at the David W. Taylor Naval Ship R&D Center is aimed at the development of overall hydrofoil structural design criteria based on past operational experience for application to future hydrofoil ships. The following discussion wil summarize the espericnced and expected trends in hull weight to meet the existing critcrin. as it effects overall ship size.

In general the hull load criteria is based on three distinct operating conditions. Hullborne, as in conventionl craft, the longitudinal bending moment in waves is the governing overall criteria. However, the longitudinal bending moment foilborne developed by the lift from the struts transmitted into the hull at two longitudinal locations normally exceeds the hullborne bending moment. Experience has shown the criteria hull loading conditions are impact pressures developed from direct wave impact on the hull while foilborne in extreme seas or from crash landings at maximum speed by direction or after loss of foil system lift.

Experience has shown that hull weight is primarily a function of total hull volume and peak local hydrodynamic impact pressures on hull bottom, sides, decks, and superstructure. Figure 28 shows actual and expected hull structural weight trends based on existing hydrofoils and design studies. Shown is Work Breakdown Structure (WBS) Groups 110 to 140 (shell plating and frames, bulkheads, decks, and platforms) and Group 110 alone. A trend of increasing structural density with shorter craft length is indicated **counter to the expected trend for** conventional craft, This reflects the governing impact pressure design conditions, as illustrated in Figure 29 for **existing craft, which** shows the gross ratio of bottom **impact area (length x hull beam) divided by hull girder volume.**

Figure 30 illustrates that WBS Group 110 weights can be expressed as a relatively constant value of the gross length times beam parameter. Correcting this relationship by a form factor accounting for the tapering of the hull forward and aft (main deck area rather than length times beam) would reduce the scatter in Figure 30. Also shown is a probable difference in Group 110 weights for single and double (continuous) second deck designs.



Fip 28 Hull girder **weights**

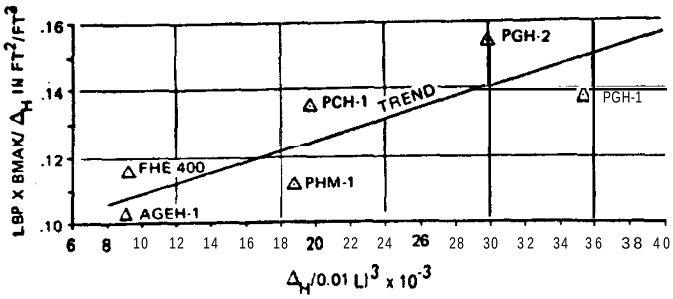


Fig. 29 Trend in hull impact area by hull girder volume for existing hydrofoil ships

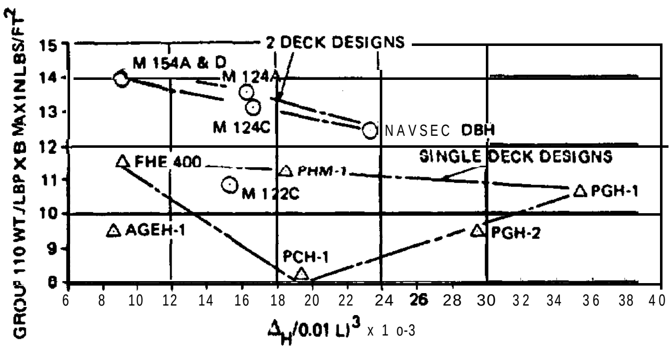


Fig. 30 Group 110 weights

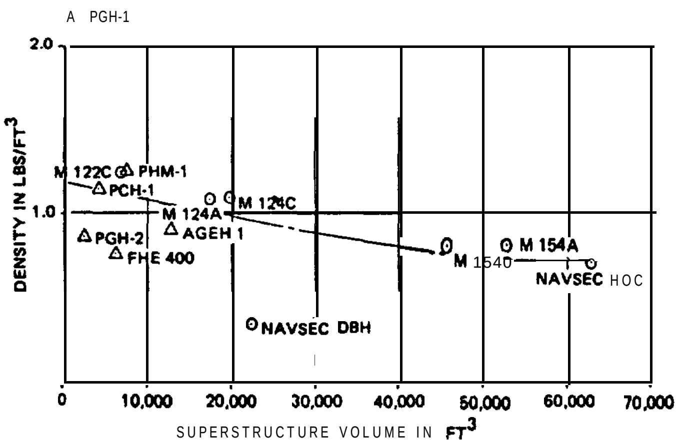


Fig. 31 Superstructure weights

Superstructure weights (WBS Group 150) are shown in Figure 31, indicating an expected increase in structural efficiency with increasing volume. To be noted are the relative structural efficiencies of the basic hull girder, Figure 28, and the superstructure.

VII. Conclusions

While the history of hydrofoil technology development has centered on the achievement and optimization of foilborne operation, the potential contribution of the (properly selected) hullform to increase overall military mission effectiveness of the total system is now receiving greater emphasis for future designs. Of the advanced ship concepts under consideration for the future Navy, the total hydrofoil system; including both the foil system and hull, probably offers the best combination of potential benefits with the least risk. The hydrofoil concept builds on the proven economies, performance, and known technology of traditional naval hullforms and combines them with the methodical developments in foil system technology of the past two decades, to extend the equally important speed and seakeeping spectrum of operations for the future Navy.

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