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EXTENDED PERFORMANCE HYDROFOILS

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Abstract

While providing about 50 percent of the Extended Performance Hydrofoil (EPH) foilborne total lift, a buoyancy/fuel (B/F) tank located below the foil system can be used for fuel, extending the hydrofoil's range well beyond that possible from comparable conventional hydrofoil designs. This capability is achieved without a large sacrifice in maximum foilborne speed. Range improvement, which increases with ship size, results basically from an increased fuel weight fraction and higher weight-to-drag ratios, particularly at lower foilborne speeds. The lower end of the foilborne speed range can be efficiently extended to 20 to 25 knots while maximum speeds greater than 40 knots are still attainable. A program for demonstrating the feasibility of the EPH concept on the Navy PCH-1 HIGH POINT R&D hydrofoil is described. It is concluded that the EPH concept will give the hydrofoil designer another option to meet specific missions, and provide new alternatives to the operator when setting forth achievable mission requirements.

Introduction

It has generally been accepted that a hydrofoil with a fully submerged foil system, referred to as a "conventional hydrofoil" in this paper, has better seaway motion characteristics than a displacement ship many times its size. Additionally, the superior speed capability of hydrofoils, even in small sizes, can be maintained in adverse weather conditions to a greater degree than larger monohulls. Since there appears to be renewed interest in small Navy ships in certain quarters, it is appropriate to examine innovations that could provide an impetus for greater utilization of the inherent advantages of the hydrofoil. For a number of years, the Naval Sea Systems Command and Naval Material Command have supported the Ship Feasibility Investigations Exploratory Development Program at the David W. Taylor Naval Ship R&D Center. These investigations have included the evaluation of a wide range of hybrid ** marine vehicle concepts [1, 2]. The most recent work has concentrated on design options which can improve the performance characteristics of hydrofoils through buoyancy enhancement.

The general concept of buoyancy enhancement of hydrofoils was discussed in reference (3). It was pointed out that range and low foilborne speed performance improvement is achieved by increasing the amount of buoyancy supporting the ship. This takes advantage of the fact that buoyant lift (from a slender submerged body) can be obtained more efficiently than dynamic lift at speeds below 30 to 35 knots.

The Extended Performance Hydrofoil (EPH) concept, illustrated in Figure 1, is one variation of hydrofoil buoyancy enhancement. Here buoyant lift, in the form of a long, slender submerged body, is combined with the dynamic lift of a fully submerged foil and strut system. Initial investigations of the EPH concept were also reported in reference (3) where it was shown that the EPH, having a buoyancy/fuel tank providing about 50% of the total foilborne lift, had a range potential well beyond that possible from a comparable conventional hydrofoil. This capability is achieved without a large sacrifice in maximum foilborne speed. Range improvement, which increases with ship size, results basically from an increased fuel weight fraction and higher weight-to-drag ratios,

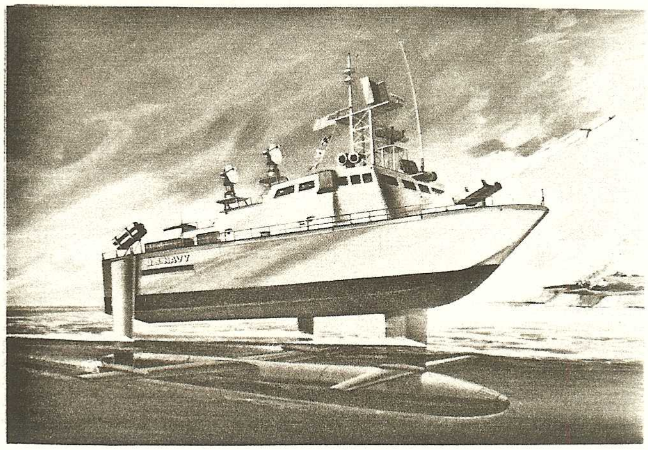

Fig. 1 Extended Performance Hydrofoil concept

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** A hybrid is defined as a marine interface vehicle having simultaneously more than one source of sustention over a major portion of its operational speed regime.

particularly at lower foilborne speeds. The lower end of the foilborne speed range can be efficiently extended to 20 to 25 knots, thus permitting operation with existing fleet and merchant ships.

This paper expands upon the work previously published particularly concerning small and intermediate size ships, and describes computer simulations and model tests of the EPH concept. Also, mission implications of the configuration are illustrated in terms of hydrofoil ferrying, team operations, a Consort mission, and a multi-mission EPH combatant. The recently established EPH Feasibility Demonstration Program is described in which the PCH-1 R&D hydrofoil is used as a test vehicle.

Parametric Investigations

To better understand the relative performance of hydrofoils with and without buoyancy/fuel (B/F) tanks, parametric investigations were made for the configuration shown in Figure 1 with propeller propulsion. Weight-to-drag ratio (hydrodynamic efficiency), fuel weight fraction, and range for different ratios of buoyancy to dynamic lift for sizes ranging from about 200 tons * to 2400 tons full load weight were examined in the speed range of 20 to 40 knots. The results clearly showed the foilborne range enhancement potential of such a hybrid form in the low speed portion of the spectrum particularly as ship size increases. For example, Figure 2 shows the weight-to-drag ratios of a hydrofoil (approximately 100% dynamic lift), a submerged B/F tank alone (100% buoyant lift) and a hybrid (50% dynamic lift, 50% buoyant lift) for different size ships. At 40 knots, the hydrofoil is more efficient than the hybrid. While at 30 knots and below, the hybrid is clearly more efficient. It is interesting to note from reference 3 that for ships as large as 4000 tons, the weight-to-drag ratios of hydrofoils and hybrids are about the same at 40 knots.

The investigations showed that in all cases, for comparable military payload ** and crew size, the Extended Performance Hydrofoil (EPH) had a higher fuel weight fraction than conventional hydrofoils. Range improvement of EPH resulted mainly from higher fuel weight fractions at the higher speeds and a combination of increased fuel weight fraction and weight-to-drag ratios at lower foilborne speeds.

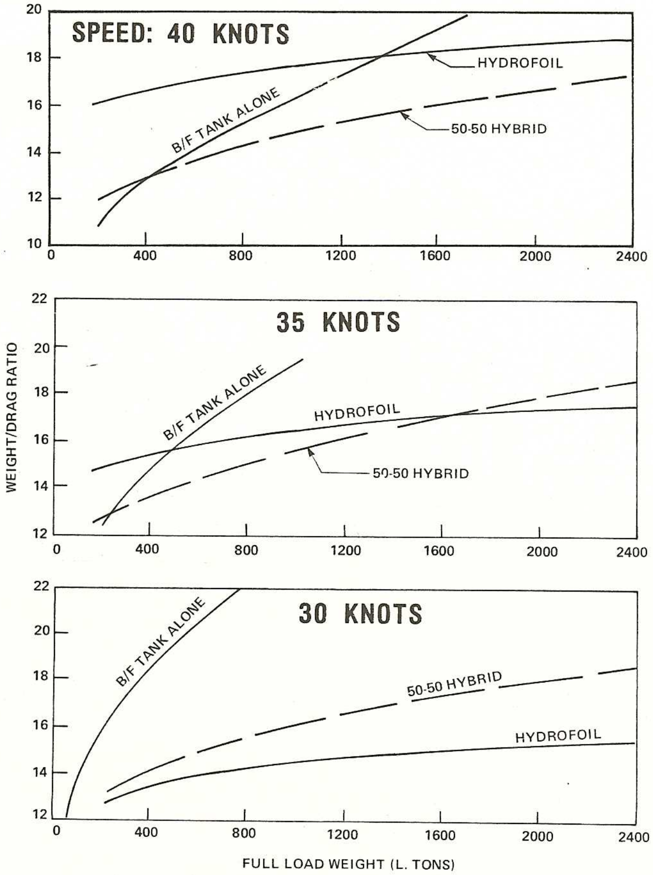

Fig. 2 Weight-to-drag ratio as a function of full load weight at 30, 35 and 40 knots

Operational Performance As A Function Of Size

Hydrofoils with and without buoyancy/fuel (B/F) tanks have been investigated to determine the relative merits of the EPH design option as a function of size. Military payload and crew size were fixed within each of four size categories. In most cases, the design speed was 40 knots in Sea State 3, however, in all cases ships were designed with strut lengths for foilborne operation in Sea State 6. The designs ‡ produced were used to determine trends of range with light-ship weight and speed. Light-ship weight was selected as a key characteristic since acquisition cost is directly related to it.

Major characteristics of the four ship size categories investigated are given in Table 1. Various size tanks were ex-

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* All references to tons in this paper are metric tons.

** Military payload includes payload portion of Group 4, Group 7, and missiles and ammunition.

‡ These designs, except for those by Grumman Aerospace Corp. used the Hydrofoil Analysis and Design (HANDE) computer program. HANDE was used directly for conventional hydrofoil design; a combined manual and computer-aided design procedure based on HANDE was developed for the design of Extended Performance Hydrofoils as described in reference (3). Note that all designs utilized propeller propulsion.

TABLE 1 - MAJOR CHARACTERISTICS OF FOUR SHIP SIZE CATEGORIES

	PAYLOAD (tons)	LIGHT SHIP WEIGHT (tons)	CREW SIZE	DYNAMIC LIFT (tons)
Small	31	150-270	21	200-500
Intermediate	80	580-1100	58	800-1720
Medium	120	750-1400	84	1350-2000
Large	240	1400-1850	140	2070-3000

amined for all size categories and it was found that those designs having buoyancy (together with foil/strut system buoyancy) of about one-half of full load weight were the most practical. This observation is illustrated in Figure 3 where the solid line for 40 knot design speed "small" conventional hydrofoils is generated by varying dynamic lift. Here, maximum foilborne range is taken at an optimal foilborne speed. A somewhat arbitrary parent ship was selected at 160 tons light-ship weight (dynamic lift of 230 tons). The dashed line shows the trend for increasing buoyancy or B/F tank size. A 200 ton displacement tank, which approaches 50% of the full load ship weight, is spotted on the trend line. It is evident from this plot that the addition of B/F tanks appreciably less than 200 tons can impact adversely on maximum foilborne range. The trend for tanks larger than 200 tons is shown. However, in all cases intact stability and its impact on the design has to be checked.

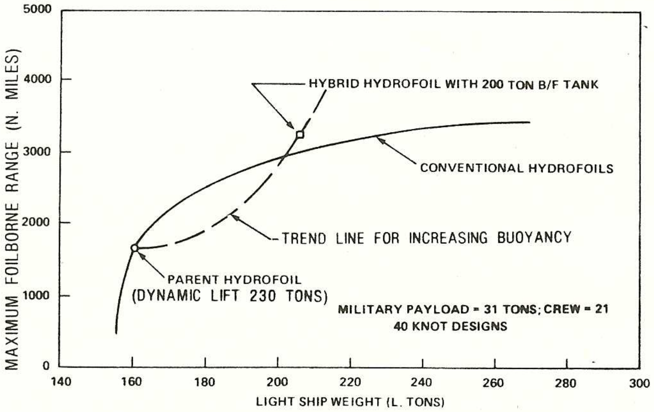

Fig 3. Maximum foilborne range at optimal speeds as a fuction of light-ship weight for small ships

Some insight into the shape of the dashed trend line for EPH with larger B/F tanks can be obtained from Figure 4. Here, a relatively large number of 40 knot "medium" size designs were explored, all with a military payload of 120 tons and a crew of 84. It is evident that just as undersized B/F tanks are undesirable so too are excessively large tanks. The latter is exemplified by the 1800 ton B/F tank on a parent hydrofoil having a dynamic lift of 1350 tons and a light-ship weight of 850 tons. The dashed trend line in Figure 4 bends over because of fixed ballast requirements and the rapid growth in propulsion and foil/strut weight.

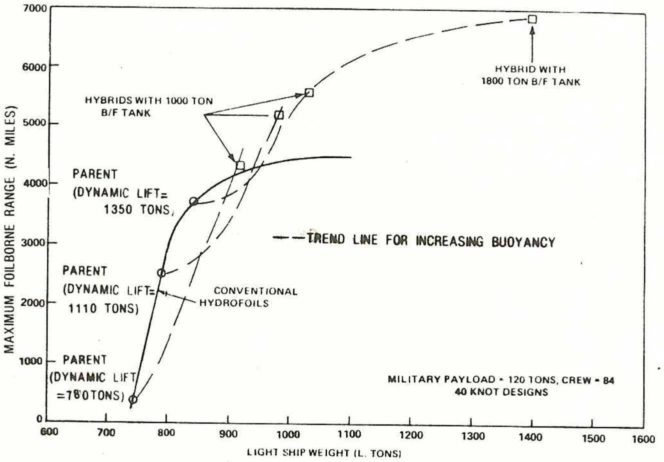

Fig. 4 Maximum foilborne range at optimal speed as a function of light-ship weight for medium size ships

Only general guidance can be provided to the EPH designer at this time as to the question: where does one start? After constructing the conventional hydrofoil maximum foilborne range vs light-ship weight trend line (for a given payload and crew requirement), a good starting point (or parent selection) appears to be at or somewhat below the "knee" of the curve. Then incorporating a B/F tank whose displacement is about equal to the parent ship's dynamic lift should provide an EPH design with a maximum range capability greater than a comparable conventional hydrofoil. "Comparable" is defined as the same light-ship weight.

Figure 3 displays another important characteristic of the Extended Performance Hydrofoil concept when compared to a conventional hydrofoil.* This characteristic is the slope * of the curves for maximum foilborne range as a function of light-ship weight in the region of relatively high range values (crossover of solid and dashed lines). For instance, the EPH (developed from the 160 ton light-ship weight parent) in the region of 3250 n. miles (or 205 tons light-ship weight) has a slope about 7 times that of a comparable (same light-ship weight) conventional hydrofoil. This

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* This slope is a measure of the increase in maximum range attainable (for a given military payload and crew) by the designer from an increase in light-ship weight through a change in dynamic lift.

means that to obtain a given range increase, the EPH requires only 1/7 the increase in light-ship weight of a conventional hydrofoil. Note in Figure 3 that the slope of the curve for this EPH is about the same as the slope of the curve at the parent ship design point. So the EPH designer has, with the appropriate proportions of buoyancy and dynamic lift, the same range improvement leverage as the hydrofoil designer had previously but now at a greater maximum range level (in the small size case, about 1500 n. miles greater). This characteristic of EPH was found to be typical of all four ship sizes investigated.

Range as a function of speed for small and intermediate size ships is shown in Figures 5 and 6. A small conventional hydrofoil and an EPH (with about 50% buoyant lift), both designs having a light-ship weight of about 205 tons, are compared in Figure 5. It is apparent that even for this size EPH, it has the potential for a maximum range somewhat greater than a comparable 40 knot maximum design speed conventional hydrofoil. At the same time this EPH has improved low speed foilborne performance in terms of efficiency of operation at the lower end of the speed spectrum. Intermediate size ships are shown in a similar plot in Figure 6. Here again, as with small ships, it is apparent that an EPH may have somewhat greater maximum range than a comparable conventional 40 knot hydrofoil.

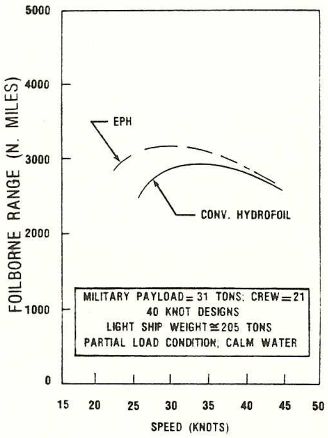

Fig. 5 Small ships

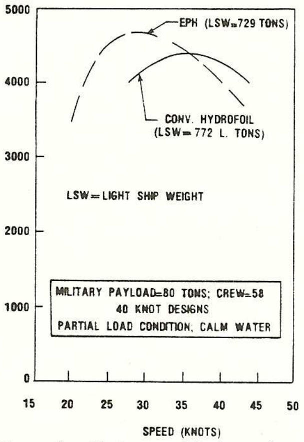

Fig. 6 Intermediate size ships

Comparison of foilborne range as a function of speed

Figure 7 depicts essentially the same range/speed characteristics for medium and large size ships taken from reference (3). Each plot shows the assumed military payload and crew. Light-ship weight and fuel weight fractions of the designs are also indicated. It should be noted that envelopes representing conventional hydrofoils in this figure are a composite of several designs.

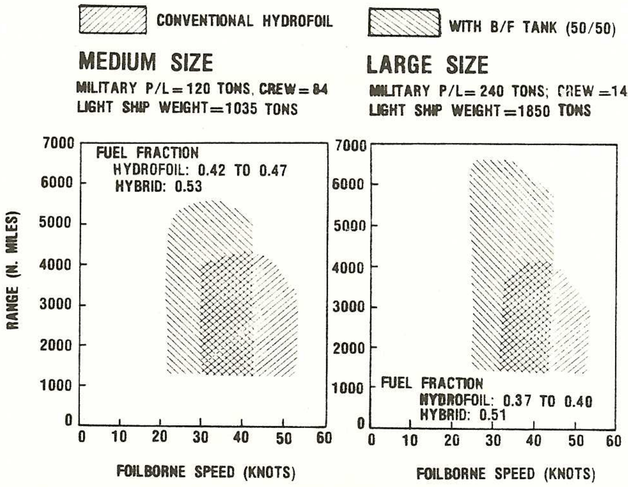

Fig. 7 Comparison of foilborne operational envelopes for hydrofoils with and without buoyancy/fuel tanks.

A cross plot of maximum foilborne range data for all size categories is shown in Figure 8. Maximum range for 40 knot hydrofoils and EPH is given in terms of light-ship weight and full load weight. To summarize the data developed in these investigations, Figure 8 shows that in all size categories explored an EPH has the potential for range improvement, particularly as size increases. In all size categories, the minimum foilborne operating speed tends to be lower for the EPH.

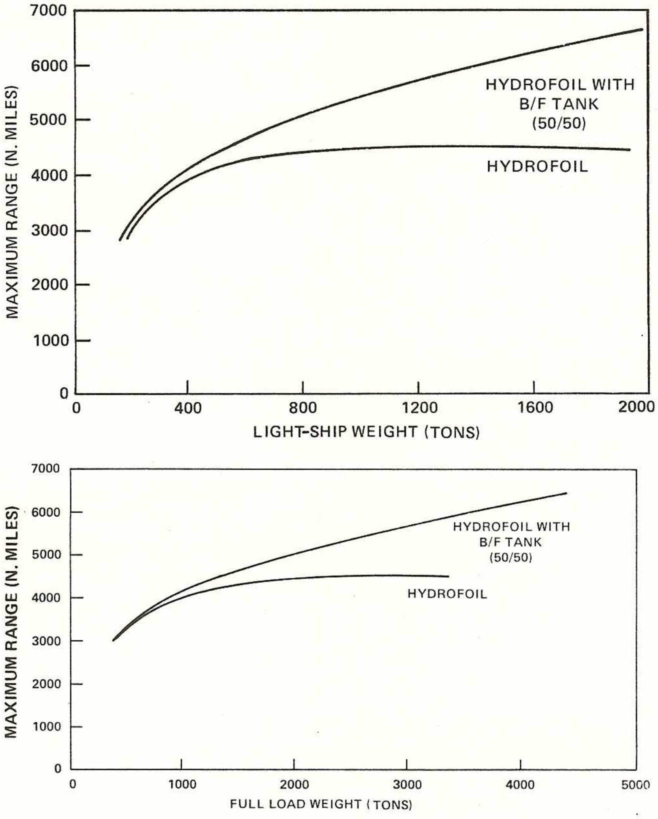

Fig. 8 Maximum foilborne range as a function of light-ship weight and full load weight for 40 knot hydrofoils with and without B/F tanks

Regarding hullborne range, estimates from reference (3) in the 10 to 20 knot speed regime have shown that hydrofoils with large buoyancy/fuel tanks are expected to have about 1.25 to 2.0 times the range of comparable (same light-ship weight) conventional hydrofoils. This is primarily because of the higher fuel fraction of the EPH, and the relatively low drag impact of the B/F tank when deeply submerged in the hullborne mode. The trend toward greater hullborne range is expected to hold true as ship size increases.

Intuitively, one would expect the power requirements for an EPH to be greater than that for a comparable conventional hydrofoil. For small ships, the EPH configuration requires about 20% more installed power for designs of comparable full load weight. However, as size increases, for designs of about 40 knots, power requirements (on the basis of shaft horsepower per ton of full load weight) were found to be about the same for intermediate size ships and even less for medium size EPH. These trends in power requirements are consistent with the results of the parametric analysis where it was shown that weight-to-drag ratios (see Figure 2) for hydrofoils with and without buoyancy enhancement at 40 knots tended to converge with increasing size. Compounded with this trend is the observation that control power for large foil systems becomes rather significant. The reader is reminded that the foil system size, and hence, control power for an EPH, is about one half of that for a comparable conventional hydrofoil (of the same light-ship weight). However, this must be balanced against some additional steering and stability control power of the EPH.

In all size categories it is, of course, necessary for the designer to consider many other factors in a detailed trade-off study. These issues, some of which detract and others that further enhance the Extended Performance Hydrofoil, are discussed in the next section.

Other Factors

The purpose of this section is to explore a number of features that must be considered by the designer in any trade-off study associated with Extended Performance Hydrofoils such as: foil/strut structural integrity, B/F tank detachability, maneuvering and control, draft, fouling of foils and B/F tank, and reduced weight sensitivity.

Foil/Strut Structural Integrity

The modified HANDE program, reference (3), was used to determine the foil/strut structural strength and its impact on weight for all EPH designs. This was believed to be adequate for this stage of the design. Loads were increased to simulate the effect of a B/F tank. Certainly, loads imposed by the B/F tank on the strut support sytem need to be examined in greater detail. Loads from the PCH-1 EPH simulations were applied to the feasibility demonstration vehicle design described in a later section of this paper. Sea trials in 1983 are expected to provide data on which future designs can be based.

B/F Tank Detachability

The questions of tank detachability-either dropping it during a mission or replacing (or exchanging) it at the dock is indeed an important issue from an operational and mission point of view. Of course, detachability would only be applicable to propulsion systems independent of the B/F tank.

Range performance can be improved by dropping the tank part way through a mission. However, the practical matters of doing this and the associated design complexities need to be explored further to determine if this is an attractive option.

Another aspect of detachability is the potential of using the tank for purposes other than carrying fuel alone. It is conceivable that such an underwater body could house sonar in the forward section or arrays could be mounted along the sides of the tank. These and other possible mission weapons equipment packages need to be pursued along with mechanical schemes for replacing the tank with minimum impact on the ship itself.

Maneuvering And Control

Maneuverability and high turn rates of conventional hydrofoils with a canard foil arrangement are achieved by banking the ship and positioning the forward steerable strut so it has little or no angle of attack in a coordinated turn. In EPH designs the additional yaw moment of the tank must be overcome by forces produced by angle of attack on fixed and steerable struts or rudders. This angle must be limited to preclude ventilation and its associated effect on directional stability.

An understanding of the maneuvering and control characteristics of the Extended Performance Hydrofoil has been approached in computer simulations and model tests. Results of motion simulations of the PCH-1 with a B/F tank indicate that in calm water no instabilities exist in response to step pitch inputs at 30 and 40 knots. Also, coordinated turns at reasonable turn rates in calm water and Sea State 5 at speeds of 25 to 40 knots were attained. More details are given in a later section of this paper.

Model tests, also described in a later

section of the paper, demonstrated good maneuverability characteristics of the EPH configuration. To achieve this, however, a controllable stern rudder was added to the model. Also, many of the maneuvers were made as partially coordinated turns.

Extended Performance Hydrofoils are anticipated to have coordinated turn rates about 75% of the maximum turn rate of conventional hydrofoils without exceeding the critical ventilation angle of attack on the struts. Partially coordinated turn rates may be somewhat higher, as indicated by recent simulation results, but further analysis and full scale tests are required to clarify this issue.

Draft

Maximum draft for an EPH will be greater than that of a comparable conventional hydrofoil in both retracted and unretracted conditions. In all cases, the EPH designs shown in this paper do not exceed a draft of 40 ft. in the wet foil retracted condition.

An examination of the differences between the navigational draft of EPH and other hydrofoils and conventional displacement ships was made. It was found that draft for the largest EPH designs (about 4000 tons) in the retracted foil condition is considerably greater than for conventional displacement naval combatants of comparable size. This condition may be alleviated somewhat if acceptable keel clearance for hydrofoil rough water operation can be reduced.

Fouling Of Foils And B/F Tank

As with current hydrofoils and larger versions being planned for the future, fouling of foil/strut systems due to marine growth has been a major concern. The approach taken by the U.S. Navy has been (except for PCH-1) to provide dry retraction even on a hydrofoil design as large as 2400 tons. Since the Extended Performance Hydrofoils discussed in this paper use wet retraction, most of them would probably have to resort to either underwater cleaning methods or dry-docking. It is conceivable that a small size EPH could be lifted from the water for foil/strut and tank cleaning and propulsion pod maintenance.

Incorporation of foil/strut dry retraction on hydrofoils with tanks could alleviate the foil/strut fouling problem. However, fouling of the tank will always remain a problem, and it will be prudent to use the most effective anti-fouling coatings available at the time an EPH goes into operational service. In this way underwater cleaning and/or dry-docking may be minimized. However, in the real world, underwater cleaning might be neglected and performance could suffer gradually over a period of years.

There are two speed regimes where fouling of underwater lift devices are critical, namely, at take-off and maximum speeds. An analysis of comparable small hydrofoils with and without a tank was made with a fouling drag coefficient of .001 (based on wetted surface area) applied to both designs. Although the EPH with a larger wetted surface area (from the B/F tank) had a greater increase in drag, this fouling represented a smaller percentage of the available 25 knot take-off margin than in the case of a comparable conventional hydrofoil. On the other hand, at 40 knots the above fouling drag coefficient on a small EPH represents a much greater increase in total drag than for a comparable small conventional hydrofoil.

Larger size ships need to be examined in some detail. However, it has been observed that relative wetted surface areas of B/F tanks (compared to foil-strut area) diminish with EPH size. Therefore, it is expected that equivalent fouling will have less impact on takeoff and maximum speeds as EPH ships increase in size.

Reduced Weight Sensitivity

In previous sections of this paper, it was pointed out that proper use of buoyancy/fuel tanks on hydrofoils can provide a large increase in hydrofoil range/endurance, and permit efficient foilborne operation at lower speeds. This section briefly describes the implication of the concept's reduced weight sensitivity.

The greater fuel weight fraction of the Extended Performance Hydrofoil designs (compared to conventional hydrofoils) allows greater flexibility in several areas without a great sacrifice in range. First, a larger payload may be added to the ship during its life, provided adequate stability, volume and deck space is available, with less impact on range performance. Second, the emphasis on using light-weight subsystems (and their relatively high cost) is reduced. This means that subsystems with an acceptable weight penalty can be used to provide improved reliability and maintainability. Third, post-construction weight growth is not as critical. In extreme cases of weight growth, the tank may even be made larger (stretched) at a small cost in top speed, rather than stretching the hull and rebuilding the entire foil system.

To illustrate the potential use of a relatively large number of less sophisticated subsystems simultaneously * on Extended Performance Hydrofoils, two versions of a 40 knot Small EPH were designed using HANDE. One version used conventional hydrofoil subsystems: aluminum hull and buoyancy/fuel tank, high-technology transmissions, gas turbine hullborne propulsion, and gas turbine driven electrical generators. The other design had less sophisticated subsystems: steel hull and buoyancy/fuel tank (but aluminum superstructure was retained), relatively lower-technology transmissions (1/2 the gear K factor ** resulting in larger size and weight), diesel hullborne prime mover, and diesel driven generators.

An attempt was also made to design a conventional hydrofoil with the same low-technology subsystems for the same mission as the low-technology EPH. Results showed that a low-technology small EPH suffered about a 33% reduction and the conventional hydrofoil greater than 75% reduction in maximum foilborne range. Furthermore, in an attempt to design a low-technology conventional hydrofoil with the same range as the low-technology Extended Performance Hydrofoil it became clear that the ship was getting increasingly large. If the desired range could have been reached, the ship would have been unacceptably large, and not competitive with the EPH. Therefore, the design was terminated before reaching the desired range. However, at that time, the length between perpendiculars of the conventional hydrofoil was about 26% greater than the EPH, its range was about 18% less and estimated cost (based on light-ship weight) was about 18% higher. It is not known at this time to what degree these results are applicable to larger size ships.

Model Experiments

During 1979 a series of experiments were performed on a 1/20 scale model of a small hydrofoil with a buoyancy/fuel tank. The basic hydrofoil model was originally designed, built and tested in 1974 by Stevens Institute of Technology (S.I.T) for the Advanced Hydrofoil Office (DTNSRDC).

Captured Model

A lower hull (B/F tank) was designed, attached to the 1/20-scale hydrofoil model strut-foil system and mounted on a force measuring apparatus, see Figure 9. In terms of full scale, the tank would produce about 200 tons of buoyant lift compared to 235 tons of dynamic lift from the foil system.

Fig. 9 Captured model of hydrofoil with B/F tank

A series of tests were carried out: first with the B/F tank alone, then with the tank and hydrofoils, and finally with tank, hydrofoils, and struts. With each setup, six components of forces and moments were measured over a range of speed, sideslip, yaw rate, depth of submergence, roll angle, pitch angle and control surface angles. The measured forces and moments were analyzed to determine various hydrodynamic coefficients defining forces and moments on the bare hull, on the hydrofoils or struts as well as interaction effects. These tests were conducted to provide a data base for development of a S.I.T Hybrid Ship Simulator. When the computer simulator is fully developed, it will provide a design tool for examining motions, maneuvering and loads of a wide variety of foil and buoyant body lift system combinations in calm and rough water.

Self-Propelled Model

Upon completion of the captured model tests, the 1/20 scale hydrofoil model was modified and rebuilt to provide self-propulsion and a fully automatic control system. The upper hull contained the electrical components including flap and rudder control servos, gyros, accelerometers and various connectors for the umbilical. The B/F tank on the model contained two major components: the propulsion system consisting of a 1-1/2 horsepower motor with a drive shaft and propeller, and a six component balance system for measuring hydrodynamic forces and moments. The model is shown in Figure 10.

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* It is realized that certain less sophisticated subsystems may be incorporated with acceptable performance penalties on a conventional hydrofoil.

** A measure of gear tooth surface stress.

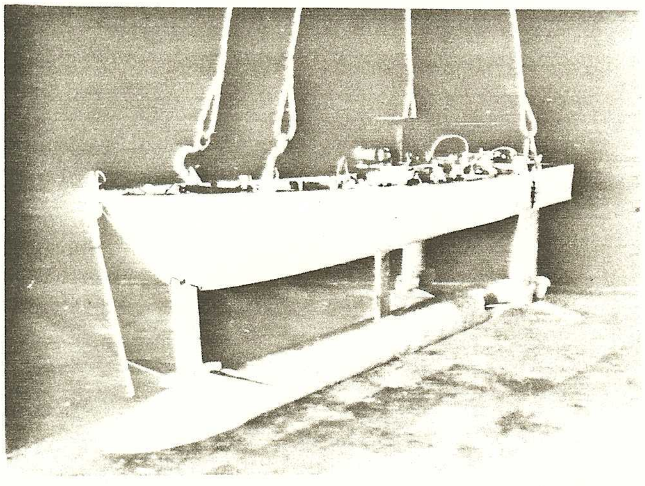


Fig. 10 1/20 scale self-propelled EPH model

The major objective of the tests was to measure the hydrodynamic loads produced by the B/F tank during maneuvers in waves. The six component balance provided information for evaluating the structural integrity of the attachment through which hydrodynamic loads would be transmitted on a full scale ship. These data were used recently for the PCH-1 EPH structural design.

A secondary objective of these experiments was to obtain motions of the model and the magnitude of control requirements imposed on the foil and rudder systems during extreme maneuvers in waves. Approximately 25 channels of data were recorded during the tests.

A four week test period was completed in the Maneuvering and Sea Keeping facility at DTNSRDC in 1979. The model was run in hullborne, semi-hullborne and foilborne modes in essentially all wave conditions up to simulated Sea State 6. Video, movies, and still photographs were taken during the tests; a picture of the model foilborne at a model speed of 8.5 knots is shown in Figure 11.

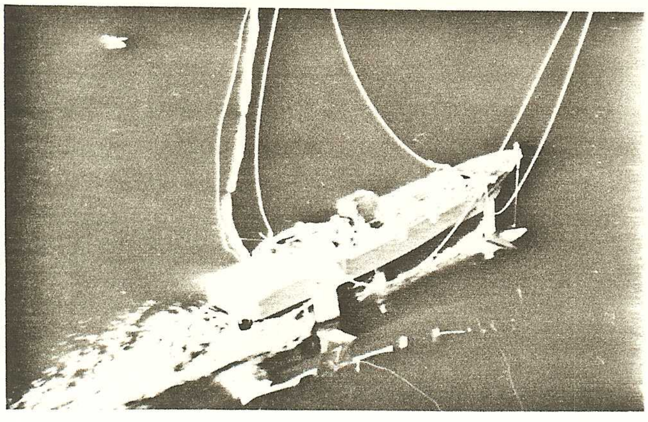


Fig. 11 Self-propelled EPH model under test in Maneuvering and Sea Keeping Facility at DTNSRDC; model speed: 8.5 knots

Mission Implications Of Extended Performance Hydrofoils

Buoyancy-enhancement of hydrofoils results in several key characteristics which contribute to the mission possibilities of EPH. These are long foilborne and/or hullborne endurance, efficient moderate-speed capability, and reduced weight sensitivity. The latter has already been discussed. This section will explore briefly moderate speed and long range open ocean transit of Extended Performance Hydrofoils, in the context of ferrying small hydrofoils over long distances, increased hydrofoil endurance thru team operations with small EPH ships, a consort/barrier role concept, and a multi-mission hydrofoil frigate.

Ferrying

This mission application relates directly to the issue of buoyancy/fuel tank detachability discussed in a previous section. An example of a ferry mission is shown in Figure 12 which illustrates how range of a small hydrofoil can be improved by attachment of a buoyancy/fuel tank and incorporating different propulsion. It is not necessary to strip the ship of its military payload. Case 2 is for a propulsion system utilizing a waterjet, whereas Case 3 is the same EPH with a propeller propulsion arrangement. All cases illustrate the relative foilborne range capabilities, however a combination of hullborne and foilborne modes would result in appreciably greater range, particularly for the EPH.

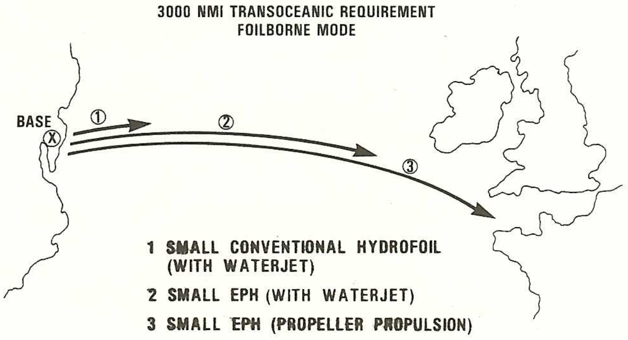


Fig. 12 Ferrying mission potential of small hydrofoils

Team Operations

An interesting operational concept for small conventional hydrofoils is to "team up" with an EPH. Shown in Figure 13 are several alternatives which illustrate the potential expansion of a small hydrofoil operating envelope. Here, for instance, it has a foilborne operational radius of R miles from a refueling base.

If 2 ships are teamed up with one EPH (all ships with waterjet propulsion) then the 3 ships could have a foilborne operational radius of 2R. It should be noted that the EPH has the same crew and military payload as the small hydrofoils but carries about 190 tons of fuel which it shares with its counterparts. EPH maximum foilborne speed, of course, is less than the conventional hydrofoil but should exceed 40 knots depending on the acceptable maximum continuous power level.

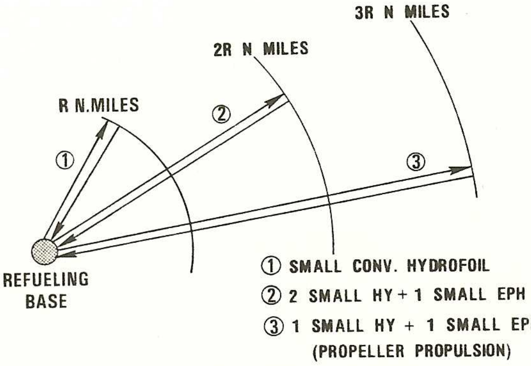
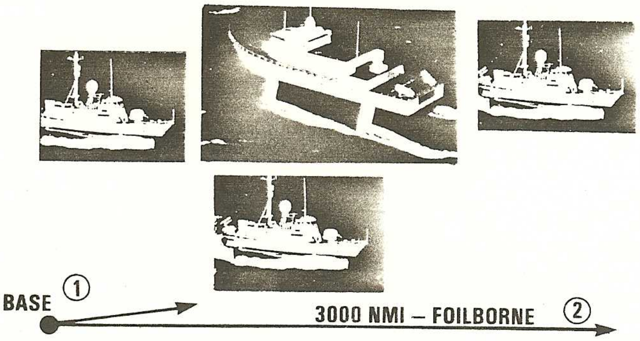


Fig. 13 EPH/conventional hydrofoil team-foilborne operations

Case 3 in Figure 13 is for a small hydrofoil teamed up with an EPH having a propeller propulsion system. As in case 2, the EPH carries about 190 tons of fuel which is sufficient for both ships to complete a foilborne mission 3R nautical miles from a refueling base. This example serves to illustrate how a conversion of two small conventional hydrofoils out of a squadron of six, for example, could give all six ships a measurable improvement in operational capability by a factor of 2 to 3.

Consort Mission

A consort role application of the EPH concept is illustrated in Figure 14 in which a next generation hydrofoil (EPH) with about a 1300-ton dynamic lift capability would operate with three small conventional hydrofoils. A global mobility capability could be realized since the EPH would provide fuel for all four ships between major refueling stops. The EPH carries its own weapon and sensor suite, and supplies missiles and ammunition, essential spares/maintenance for the hydrofoils and medical aid for all four crews. Upon deployment in a barrier type mission, the EPH would continue to support the hydrofoils while at the same time playing its part in the barrier mission.



① SMALL CONVENTIONAL HYDROFOIL

② CONSORT EPH + 3 SMALL HYDROFOILS

- CONSORT EPH SUPPLIES:
  - – FUEL
  - – MISSILES AND AMMUNITION
  - – ESSENTIAL SPARES/MAINTENANCE
  - – MEDICAL AID

Fig. 14 EPH in consort role with conventional hydrofoils for global mobility

Multi-Mission EPH Combatant

A recent study focused on a future-generation multi-mission EPH combatant for the 1990-1995 time frame. Because of its high speed, long endurance and combat payload, an EPH (having about a 1350 ton dynamic lift system) shown in Figure 15 has the potential to become a truly multi-mission escort for high speed and high-value convoys and naval forces. Several scenarios were selected to reflect such missions and the following conclusions were drawn. The ability of the EPH to operate at high speed with ranges comparable to those of slower displacement ships would make it well suited as an ASW/AAW escort for trans-oceanic convoys and fast mobile logistic groups during open-ocean transits. Although small, the EPH, equipped with advanced ASW and AAW systems, could perform a number of escort missions as well as, and at higher speeds than, modern frigates. This would remain true even if the existing frigates were up-graded with the same advanced weapon

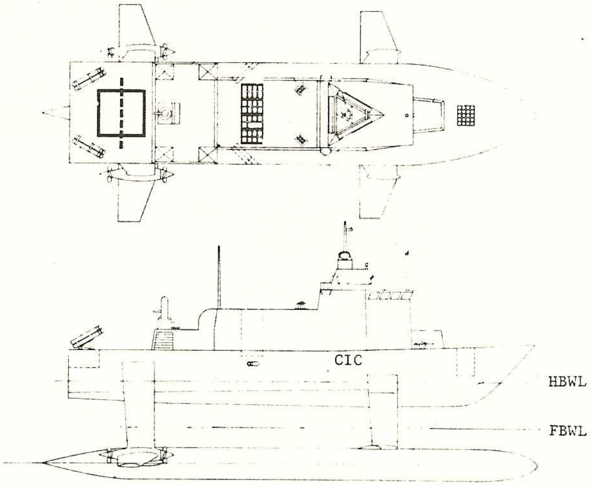


Fig. 15 Multi-Mission EPH Combatant

and sensor systems as the EPH. Operationally, the EPH was shown to be superior to displacement ship combatants in cases where high sprint speed or high sustained SOA complement the capabilities of the advanced weapon suite and meet the needs of the force being escorted.

This particular mission analysis is briefly mentioned here only to illustrate the potential of the EPH concept in a 2600 ton size ship.

Feasibility Demonstration

The PCH-1 HIGH POINT hydrofoil was selected in 1979 as the R&D vehicle for feasibility demonstration of the EPH concept under the Navy's exploratory development program. Since that time, a series of feasibility designs and analyses of critical areas were performed to minimize uncertainties, reduce the technical risk and provide high confidence in success of the demonstration vehicle. This section of the paper will briefly describe the vehicle, motion and loads simulations, plans for construction and sea trials of the EPH demonstrator in 1982 and 1983.

Craft Description

The PCH-1 is a canard configured hydrofoil craft with the following principal characteristics, exclusive of the buoyancy/fuel tank:

L.B.P	110.00 ft.	(33.53 m.)
Length Overall	115.75 ft.	(35.28 m.)
Beam - (Maximum)	31.28 ft.	(9.53 m.)
Beam - (DWL)	21.40 ft.	(6.52 m.)
Draft - (Foils Ext.)	19.83 ft.	(6.04 m.)
Draft - (Foils Ret.)	8.58 ft.	(2.62 m.)
Displacement - (Light Ship)		108.00 tons
Displacement - (Full Load)		131.00 tons

With the addition of a 66-ton tank to the craft, the drafts and displacements are as follows:

Draft - (Foils Ext)	22.33 ft.	(6.81 m.)
Displacement - (Light Ship)		132.00 tons
Displacement-(FullLoad-Fuel)		200.00 tons

The existing strut/foil installations are arranged for wet retraction. Retraction of the struts with the B/F tank installed is possible as there is no permanent attachment between the B/F tank and the strut/foil system. Propulsion is provided by two Proteus PT1273 gas turbine engines driving four (4) five bladed sub-cavitating fixed pitch propellers through bevel gears and strut shafting. The tank is attached to the underside of the hull as shown in Figure 16. The attachments are designed so that loads in all axes are resisted at the midship strut, the aft foil connection being capable of taking side and vertical up loads only. To enhance the tank stability and craft steering, an additional rudder is added at the tank centerline aft.

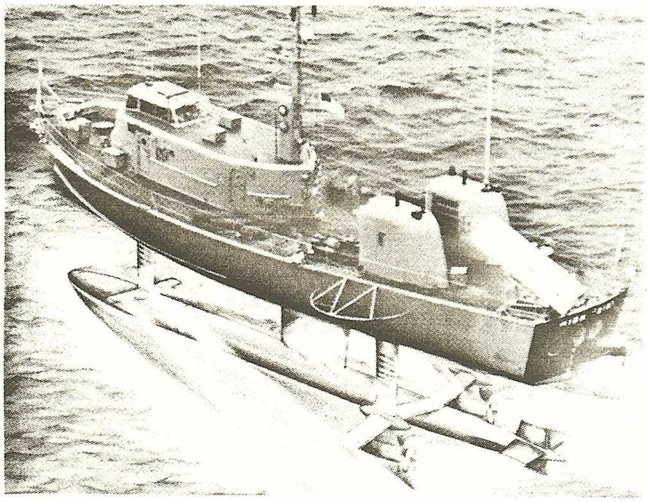


Fig. 16 PCH-1 HIGH POINT EPH feasibility demonstrator

Fuel and ballast are contained within the same tank compartments, separated by horizontal flexible diaphragms. Displacement of either fuel or ballast is accomplished by pressurizing the opposite side of the diaphragm, utilizing ram pressure on the ballast side foil-borne, static pressure hullborne, and an existing fuel pump or pressure fueling on the fuel side. Segregation of fuel cells is provided by separate fill/discharge lines.

Motion And Loads Simulation

A computer simulation of the PCH-1 EPH feasibility demonstration craft was developed at DTNSRDC. The purpose was to determine the craft's motions and the loads developed by the tank under a variety of conditions within the anticipated operating envelope using the present autopilot. The dynamic, digital simulation was constructed by merging an existing six degree of freedom simulation of PCH-1 (having no autopilot changes) with a simulation of the tank assembly.

The objectives of this simulation were to:

1. Establish the mathematical structure and gains of the tank rudder command,

2. Estimate the likelihood that venting or cavitation will occur, especially for the vertically-oriented lifting surfaces,

3. Evaluate motion and maneuvering characteristics in calm water and waves,

4. Compare performance of the PCH-1 EPH to that of PCH-1 without a tank,

5. Determine the internal force and couple acting at the support strut and hull interface,

6. Estimate the habitability characteristics of EPH, particularly in terms of translational accelerations at selected points,

7. Determine the effect of the tank rudder (and horizontal stabilizer),

8. Evaluate and compare analytic and experimental models for the submerged, load-carrying structure.

Results of the simulation showed that the vertical member of the cruciform stern, being an active control surface for EPH, must be commanded to move in a way ensuring overall stability, and overcoming part or all of the adverse effects of the tank's presence, especially in turns.

It was found that the craft was stable foilborne in the vertical plane in response to a number of height and pitch step inputs made in calm water. For the horizontal plane, runs were made at speeds from 25 to 40 knots, Sea States 5 and 6, straight line and turns from helm commands of 90 and 135 degrees - with and without the tank in some cases for comparison purposes. Although the tank degrades turn performance, the simulation shows that turn radius increases by only about 15%, and increases somewhat the average control surface angles.

A check of habitability was made by computing selected statistics for components of the translational acceleration of a point on EPH corresponding to the PCH-1 center of gravity. This was done for a mid-range speed of 35 knots at headings of 000, 045, 090, and 135 degrees, in Sea State 5 and at a heading of 000 in Sea State 6. Predicted motions agree quite closely with those of the PCH-1 without a tank.

Time histories and statistical measures of components of the internal force and couple associated with the support strut/hull junction were computed for the seaway runs using a dynamic model of the tank assembly. These loads, together with the data collected during the self-propelled model tests, provided a rationale for full scale loads analysis and structural design.

Construction And Trials

Upon completion of the detail design of major components of the PCH-1 EPH, construction of the B/F tank and modification of the PCH-1 hull are planned at the Puget Sound Naval Shipyard during FY 1982. Launch and dock trials are scheduled for early FY 1983. This will be followed by sea trials during the remainder of the year. Objectives of the trials are:

1. Demonstrate the feasibility of operating the EPH concept in hullborne and foilborne modes in waves up to mid Sea State 5. The maximum foilborne speed expected is about 40 knots in calm water.

2. Verify technical analyses and model experiments.

3. Acquire data on EPH tank loads in addition to the usual parameters measured during PCH-1 trials to produce a data base adequate to design and operate future and larger EPH ships.

Conclusions

1. Parametric analyses clearly illustrate the foilborne range enhancement potential of Extended Performance Hydrofoils (EPH) in the 20 to 35-knot speed regime, particularly as size increases. In all cases EPH configurations tend to have a higher fuel weight fraction than comparable conventional hydrofoil designs.

2. Minimum, efficient foilborne speeds of EPH are at least 5 knots lower than conventional hydrofoils for all sizes examined.

3. In small and intermediate sizes, 40 knot EPH designs have somewhat greater maximum foilborne range potential than comparable conventional hydrofoils.

4. In medium and large sizes, the maximum range of EPH is considerably greater than a hydrofoil without a buoyancy/fuel tank over the entire foilborne speed spectrum.

5. Maximum speeds of EPH are anticipated to be greater than 40 knots, but lower than those of conventional hydrofoils.

6. Tank detachability has some advantages for small hydrofoils for ferrying. However, this issue requires more detailed attention for larger ships having broader mission requirements.

7. Analyses of the controllability and maneuverability of EPH indicate that no instabilities exist, and coordinated turn rates are expected to be about 75% of a comparable conventional hydrofoil.

8. Extended Performance Hydrofoils have reduced weight sensitivity with potential for utilizing heavier conventional subsystems resulting in a potential for greater reliability and reduced maintenance. They are less sensitive to postconstruction weight growth.

9. Because of its greater take-off thrust margin, the EPH can tolerate more foil system and tank fouling than conventional hydrofoils.

10. Good moderate speed performance, long hullborne and foilborne range potential, in all sizes, should make the concept effective in current fleet missions. Even in small sizes long range/high endurance foilborne missions, such as open ocean transits, are feasible.

11. Model testing, computer simulations, loads analysis and design effort to date indicate that the PCH-1 EPH Feasibility Demonstration Program should be successful and provide a strong data base for the design of future hydrofoils.

12. The Extended Performance Hydrofoil gives the hydrofoil designer another option to meet specific missions. It also provides new alternatives to the operator when setting forth achievable mission requirements.

Acknowledgement

This paper is the culmination of several years of work on the part of a number of DTNSRDC personnel and others. Particular credit is given to J. King and W. O'Neill of the Advanced Hydrofoil Systems Office, G. Karafiath, T. Moran, J. Russ, F. Peterson, A. Gersten and R. Messalle of the Ship Performance Department, W. Buckley, P. Yarnell, and J. Andrews of the Structures Department; all of whom have made technical contributions to this program. Credit is also due to the Davidson Laboratory staff of Stevens Institute of Technology who designed, built and tested the model described in this paper. Additionally, the early EPH feasibility analyses and recent EPH detail design work of the Grumman Aerospace Corp. is recognized. Certain mission analyses by Battelle Memorial Institute and R.E. Adler Consultants, Inc. is also commended.

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