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THE HYDROFOIL SMALL WATERPLANE AREA SHIP (HYSWAS)

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Abstract

The paper presents a summary of concept investigations of a hybrid surface vehicle - the Hydrofoil Small Waterplane Area Ship (HYSWAS). This hybrid consists of a single submerged hull with a fully-submerged foil system and an upper hull structure supported above the water surface by a relatively thin longitudinal strut. In the low speed (hullborne) mode, sustention is provided by buoyancy of the submerged hull, the strut, and a small segment of the upper hull. As speed is increased, the dynamic lift of the foil system raises the upper hull above the water and the waterplane area of the strut becomes small. Performance, stability and control, structures, propulsion, and ship system engineering including a weapons suite of a 2,000-ton (2,032 m. ton) HYSWAS with 70% buoyancy and 30% dynamic lift are discussed. It is concluded that this ship, with 50,000 to 60,000 hp installed, would have a maximum speed between 42 and 45 knots, and good range/endurance characteristics with about 180 tons (183 m. tons) of military payload. Foilborne roll control is predicted to be adequate down to calm water speeds of about 16 to 18 knots, satisfactory pitch/heave stability is indicated through maximum speed, and it is expected that heave and pitch motions of HYSWAS when foilborne will be superior to conventional monohulls in head seas. Arrangements studies and weight estimates show that this particular HYSWAS design has a volume conducive to general arrangement flexibility and a relatively large useful load fraction. At this early stage of development, the HYSWAS hybrid form, in a 2,000-ton size, combines many desirable characteristics in a single platform, and therefore appears to be a candidate for small, open-ocean, all-weather, naval combatants.

Introduction

The Hydrofoil Small Waterplane Area Ship (RYSWAS) concept is an outgrowth of a Hybrid Marine Interface Vehicle Program initiated at the David W. Taylor Naval Ship Research and Development Center in 1973. One of the objectives of this program is to identify and assess the potential benefits of conceptual hybrid† surface ship platforms having a variety of lift combinations. The concept of the hybrid "Sustention Triangle" was introduced by Jewell[1] who set forth a systematic scheme of categorization of vehicles by their source of lift. A hybrid vehicle can be conveniently represented in terms of three quantities: x, y, and z, whose integer values represent tenths of total weight supported by unpowered static lift (buoyancy), dynamic lift, and powered static lift, respectively. For example, a hybrid ship having 70% buoyancy, 30% dynamic lift, and no powered static lift is designated as a (7,3,0) hybrid.

Several 2,000-ton hybrid configurations have been examined to compare speed and range performance in both calm and rough water.[2,3] The hybrid forms analyzed included Small Water-plane Area Single-Hull Ship (SWASH), Hydrofoil Small Waterplane Area Ship (HYSWAS), Large Hydrofoil Hybrid Ship (LAHHS), Hydrofoil Air Cushion Ship (HYACS), and Small Waterplane Area Air Cushion Ship (SWAACS), illustrated in Figure 1. Analysis showed that the

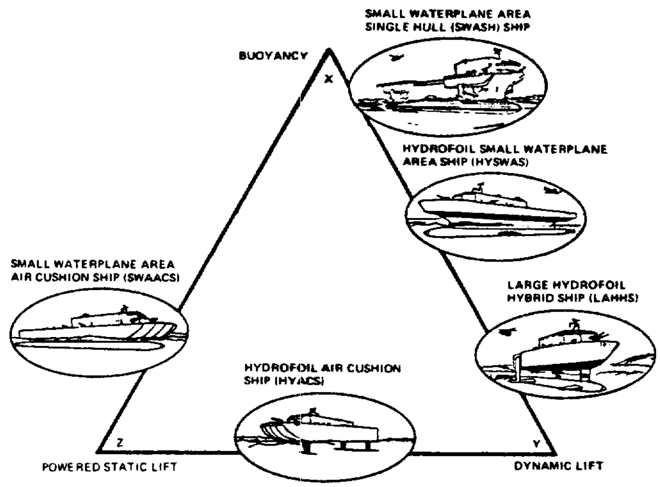

FIGURE 1 - SUSTENTION TRIANGLE WITH HYBRID CONCEPTS

HYSWAS concept offers generally favorable performance characteristics in calm and rough water over a broad speed spectrum. For special purpose missions where, for instance, a segment of the speed spectrum is dominant or rough water operations are not of primary importance, other hybrid forms may show potential and should be pursued further.

A more detailed examination of the 2,000-ton HYSWAS concept was made wherein designs having 20% to 40% dynamic lift and lower hull length-to-diameter (ℓ/d) ratios of 12 to 20 were investigated.[4] A 2,000-ton size was selected primarily because of Navy interest in advanced vehicles in this size. Furthermore, it was anticipated that this size ship would provide a viable military payload and trans-Atlantic range at a relatively high speed with a reasonable size power plant. In the case of HYSWAS. feasibility studies are also being made of other sizes ranging from 1,000 tons (1,016-m. tons) to 4,000 tons (4,063 m. tons)

Although no specific mission analyses have been performed for any HYSWAS designs to date, the rationale for size,, payload, weapon suite, manning, speed, and range has been derived from other studies. It is believed that there is a need for a surface ship system with all of the following characteristics combined in a Single platform:

- Maximum speeds up to 40-50 knots (depending on size) and the ability to sustain these speeds in rough water,
- Efficient operation at both low speed and high speed; eliminate the hump in the power curve,
- Good range characteristics throughout the speed regime; range should not decrease

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

at speeds below design speed, but rather increase. Range should be comparable to that of larger displacement ships,

. Pitch and heave motions superior to conventional monohulls in large head seas, and hence, good seakeeping,

. Large useful load fraction; volume should be conducive to general arrangement flexibility.

HYSWAS is a cross between a fully-submerged hydrofoil and a demi-SWATH (Small Waterplane Area Twin Hull) ship, and therefore all analytical investigations have relied heavily upon the technology of these two parent forms. It is emphasized that no tests have been performed on HYSWAS, but as the investigation matured, certain properties of the configuration became evident. The purpose of this paper is to describe what has been learned about HYSWAS in the area of hydrodynamics, performance, structures, propulsion, certain subsystems, and general arrangements.

Description of HYSWAS

HYSWAS consists of a single slender submerged hull equipped with a fully-submerged, automatically-controlled foil system, and an upper hull joined to the submerged hull by a thin, longitudinal strut. The concept is illustrated in Figure 2 which shows the waterlines for hullborne and foilborne operation.

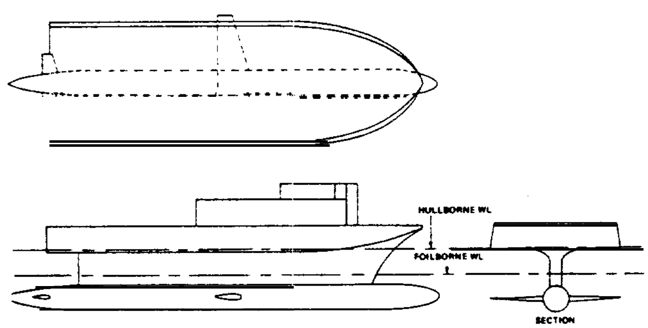

FIGURE 2 -SKETCH OF THE HYDROFOIL SMALL WATERPLANE AREA SHIP (HYSWAS) FORM.

In the low speed (hullborne) mode, buoyancy is provided by the submerged hull, the strut, and a small segment of the upper hull. As speed increases, the foil lift raises the upper hull above the water and the waterplane area becomes small. The weight of the ship is supported by buoyancy and hydrodynamic lift. HYSWAS is predicted to operate at higher lift-to-drag ratios (L/D) than hydrofoils at the lower end of the foilborne speed range and at higher L/D's than displacement ships in the high end of the speed range.

An inherent limitation of the HYSWAS configuration is its relatively deep draft (for a given displacement) in the hullborne mode. This can vary from about 30 feet (9.1 m) to 40 feet (12.2 m) for 1,000- to 4,000-ton designs; however, recourse to an elliptical hull can reduce the draft by 2 to 4 feet (0.6 to 1.2.m). Foilborne drafts range from 18 to 27 feet (5.5 to 8.2 m). Compared to monohulls, HYSWAS designs require accurate weight and balance predictions and control of same during design, construction, and operation.

Assuming that a broad operating speed spectrum is desired, a hybrid combination of about 70% buoyant lift and 30% dynamic lift at design conditions is found to provide good hydrodynamic qualities. Minimum foilborne speeds for HYSWAS with a relatively large buoyant contribution, can vary from about 16 to 23 knots depending on the foil loading (or waterline level) selected by the operator.

From stability considerations, described later in the paper, the upper hull of HYSWAS requires greater beam than conventional monohulls and hydrofoils, but is narrower than SWATH or low length-to-beam Surface Effect Ships (SES) of comparable displacement. SWATH ship designs have demonstrated the hydrodynamic advantages of lower hull length-to-diameter ratios (ℓ/d) greater than about 12 (and preferably 14 to 16) and this has been an important factor in determining HYSWAS strut and lower hull proportions. Conceptual HYSWAS studies covered L/d ratios from 12 to 20.

TABLE 1
SUMMARY OF PHYSICAL CHARACTERISTICS
FOR A 2,000-TON (7,3,0)
HYDROFOIL SMALL WATER PLANE AREA SHIP (HYSWAS)

Full Load Displacement	2,000 tons	2.032 m. tons
Design Buoyancy	1,400 tons	1,422 m. tons
Design Foil Lift	600 tons	610 m. tons
Lower Hull Length	267 feet	78.3 m
Lower Hull Diameter	16.4 fnt	4.7 m
Lower Hull Buoyancy	1,130 tons	1.148 m. tom
Lower Hull Material	Aluminum	
Strut Length	180 feet	54.9 m
Strut Thickness	7.2 feet	2.2 m
Strut Immersion Factor	2.5 tons per inch	1.0 m ton per cm
Strut Buoyancy at Rest	630 tons	640 m. tons
Strut Height	19.7 feet	6.0 m
Strut Material	Aluminum	
Main Foil Area	850 feet2	79 m^2
Main Foil Span (Tip-to-Tip)	87 feet	26.5 m
Main Foil Average Chord	12 feet	3.7 m
Main Foil Location	Approximately 110 feet (33.5 m) from lower hull bow	
Aft Foil Area	270 feet2	25.1 m^2
Aft Foil Span (Tip-to-Tip)	40 feet	12.2 m
Aft Foil Average Chord	8.2 feet	2.5 m
Aft Foil Location	Approximately 235 feet (71.6 ml from lower hull bow	
Total Foil Buoyancy	30 tons	30.5 m. tons
Upper Hull Length	234 feet	71.3 m
Upper Hull Beam-Max.	78.8 feet	24.0 m
Upper Hull Depth	15 feet	4.6 m
Upper Hull Buoyancy at Rest	210 tons	213 m. tons
Upper Hull Material	Aluminum	
Hullborne Draft	35.1 feet	10.7 m
Foilborne Draft (1,200 psf Foil Loading)	23.1 feet	7.3 m

Table 1 shows some of the physical characteristics of the 2,000-ton HYSWAS illustrated in Figure 3. A variety of foil arrangements was investigated; however, a conventional (airplane-type) arrangement with a 75%-25% lift distribution

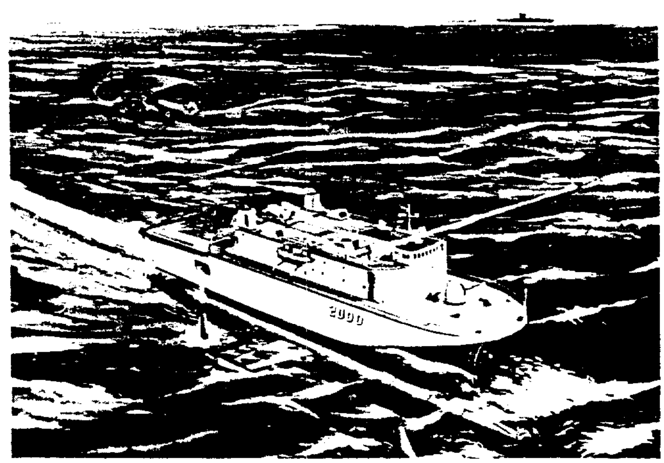

FIGURE 3 - HYDROFOIL SMALL WATERPLANE AREA SHIP (HYSWAS)

on the main and aft foils respectively appears to offer certain advantages. The main foil is located at about midships just forward of the center of gravity; the aft foil is about one chord-length forward of the propellers. The ship is all aluminum and arranged to accommodate a crew of 118, two LAMPS size helicopters, and a weapon system, selected for illustrative purposes, consisting of a 76 mm Oto Melara gun, two CIWS Gatling type guns, two four-canister Harpoon launchers, one eight-canister NATO Seasparrow launcher, and two MK-32 torpedo launchers. Weight and space for bow mounted sonar is provided in the lower hull. The selected main propulsion system consists of two LM 2500 gas turbine engines (space is available for two FT-9 engines as alternative power plants) located in the upper hull, a Z-Drive bevel gear system which transmits power through the strut to a contrarotating planetary reduction gear and fixed-pitch contrarotating propellers. Auxiliary propulsion is provided for harbor and low speed hullborne operation. A weight estimate summary for the ship is given in Table 2. Structures, propulsion, and ship systems engineering are discussed in greater detail later in the paper.

TAHLE 2
2,000-TON HYSWAS COMBATANT WEIGHT ESTIMATE SUMMARY
(Normal Load)

Group	WEIGHT Long Tons	Metric Tons	Percent
1. Hull Structure	455	462	22.6
2. Propulsion	160	163	9.0
3. Electric Plant	63	64	3.2
4. Communications	88	89	4.4
5. Total Auxiliary	235	239	11.7
Less Foils	148	150	7.4
Foils	87	89	4.3
6. Outfit & Furnishings	145	147	7.2
7. Weapons	34	35	1.7
Total Light Ship	1,200	1,219	60.0
15% Margin	180	163	9.0
Ship Fuel	508	516	25.4
Helo Fuel	20	20	1.0
Variable Loads	56	59	2.9
Ammunition	22	23	1.1
Helicopters	13	13	0.6
Total Full Lmd	2,001	2.033	100.0
Payload (GRP4, GRP7, Helo Fuel, Ammunition, Helicopters)	177	180	8.8

The normal center of gravity is 130 feet (39 6 m) aft of the lower hull nose and 30 5 feet (9.3 m) above the keel

In an overload condition, the fuel weight increases to 670 tons (681 m tons) and the ship weight increases to 2.163 ton (2,197 m. tons). The overload center of gravity is 127 feet 138.7 m) aft of the lower hull nose and 29.8 feet (9.1 m) above the keel

Hydrodynamics

During the early phases of the hybrid vehicle investigation, considerable thought was given to not only improving speed/range performance over a broad speed spectrum (up to 45 or 50 knots), but also providing seakeeping characteristics superior to monohulls in the 2,000-ton category. It was evident that both the Small Waterplane Area Twin Hull (SWATH) ship and fully-submerged hydrofoil forms could benefit the latter, but neither, by itself, could promise improved hydrodynamic efficiency over the entire speed range. SWAT-I ships have hydrodynamic characteristics generally similar to conventional displacement ships wherein drag tends to increase sharply at high Froude numbers. Hydrofoils have relatively good drag characteristics at high speeds, but the designer of large hydrofoils is challenged in at least two areas: how to alleviate the hump drag at speeds where the rest of the fleet will operate much of the time, and how to cope with an ever increasing foil-span-to-hull-beam ratio with ship size. HYSWAS was therefore conceived as a hybrid to obtain the benefits of both the SWATH form and the fully-submerged hydrofoil without certain hydrodynamic disadvantages of either parent. The synergistic hybridization process provided not only the anticipated benefits, but some unexpected ones as well.

The hydrodynamic characteristics of a specific HYSWAS design are discussed under the following major topics: Speed-Power; Range and Endurance; Stability, Control, and Motions; and Maneuvering.

Speed-Power

Drag and speed-power characteristics are obtained from a computer program[5] developed for hybrid ships; the program has been used for a wide variety of HYSWAS configurations. The HYSWAS designs considered to date have a design foil loading of 1,200 psf (5,859 kg/m^2). However, HYSWAS, with a relatively large proportion of buoyancy, has an inherent capability of providing improved lift-to-drag (L/D) ratios when operating below design speeds under full-load conditions. This characteristic is shown in Figure 4 where, for this particular 2,000-

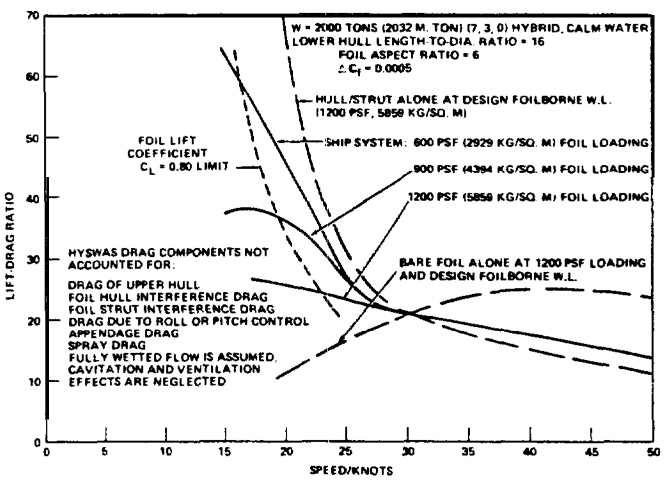

FIGURE 4 - HYSWAS LIFT-DRAG RATIO

ton HYSWAS design, reduced foil loading is traded off for increased strut immersion resulting in higher L/D's and a capability of operating with partial foil lift at speeds below 30 knots. This was an unexpected result of the HYSWAS hybrid form. Figure 4 indicates that at foil loadings of 600 psf (2,929 kg/m^2), this configuration could achieve calm water L/D ratios from 58 to 22 between speeds of 16 and 30 knots. However, determination of limits on operation at reduced foil loadings in a real ocean environment requires model testing in waves. Figure 4 also shows L/D curves for the bare foil alone at 1,200 psf (5,859 kg/m^2) loading and the hull/strut alone operating at the design foilborne waterline. These curves indicate the bounds of possible L/D values for HYSWAS and serve to clarify why this concept in a (7,3,0) hybrid form has relatively favorable L/D's over the entire foilborne speed spectrum from about 16 to 50 knots. A limit line, in terms of a maximum operating lift coefficient of 0.80, is shown on Figure 4 to define speeds below which foilborne operations (at a particular foil loading) are not advisable.

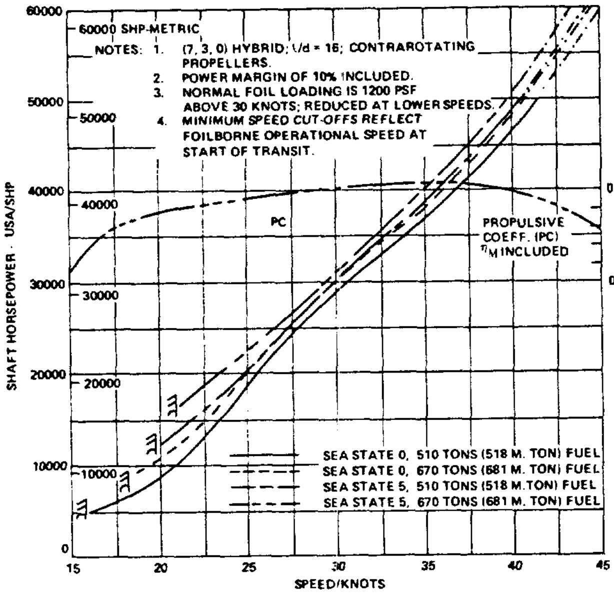

FIGURE 5 - SPEED POWER OF A 2000-TON HYSWAS

Figure 5 shows the estimated power required for this 2,000-ton HYSWAS design under a variety of conditions. The propulsive coefficient (P.C.) curve used for these estimates is also shown. A power margin of 10% is used to account for various quantities, such as certain interference effects, control drag, spray drag, and cavitation effects, not included in the drag analysis. A maximum speed of 42 knots is obtained using two LM 2500 gas turbine engines (maximum continuous power of 25,000 hp (25,350 m. hp) each at 80°F (27°C)). From Figure 5 it can be seen that the power hump has been virtually eliminated. This provides economical, continuous, and controlled foilborne operation in calm water from about 16 knots through the maximum speed of the ship.

Although calm water has traditionally been used as a basis for performance comparisons, it must be recognized that rough water in terms of Sea State 5 (significant wave height, $H_{1/3}$ = 8 ft., 2.44 m) and above may occur about 50% of the time in the North Atlantic (above 30" N. latitude, or Jacksonville, Florida).[6] Realizing the importance of rough water operations, power degradation/speed penalty information for various ships was collected[3] and used to estimate rough water power curves in mid-Sea State 5 ($H_{1/3}$ = 10 ft., 3.05 m) head sea conditions for this particular HYSWAS as shown in Figure 5. Power estimates for an alternate fuel load (discussed later in the paper) are also shown. The power penalty in general is not large, except in the low speed range around 20 knots where power required is sensitive to foil loading and, hence, upper hull clearance. Experiments are required to clarify upper hull clearance requirements for HYSWAS in large waves under various load conditions.

Range and Endurance

A normal fuel load of about 510 tons (518 m. tons) for this specific HYSWAS design is derived from a weight analysis (See Table 2). This fuel load corresponds to a military payload of 177 tons (180 m. tons) in addition to the variable loads of 58 tons. Payload is defined as the total of GROUP 4 (Communication and Control), GROUP 7 (Weapons Systems), ship ammunition. helicopters, and helicopter fuel. Variable loads include such items as crew and effects, stores, potable water, and lube oil.

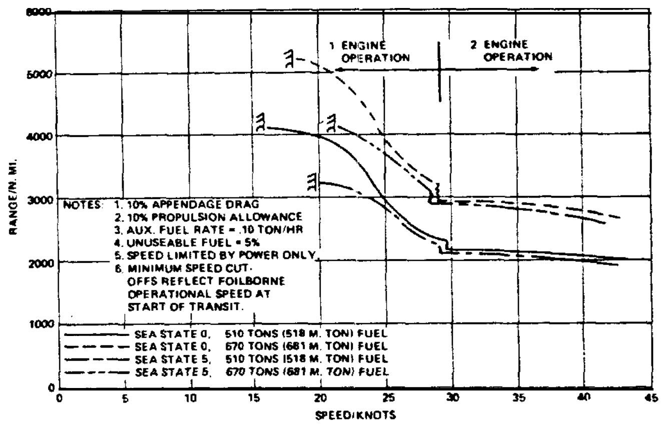

FIGURE G - ESTIMATED RANGE OF A 2000-TON HYSWAS: PAYLOAD = 177 TONS (180 M. TON)

Results of the calm water range calculation with 510 tons (518 m. tons) of fuel are shown in Figure 6. A propulsion allowance of 10% (to account for propulsion system degradation and hull aging), an auxiliary fuel rate (or hotel load) of .10 ton/hr., and an unuseable fuel factor of 5% are assumed. Variations in specific fuel consumption (sfc) with power are taken into account. Constant weight with fuel burn-off is assumed because HYSWAS has a requirement, for reasons that will be discussed later, to take on ballast to maintain intact stability. At a normal fuel load of 510 tons (518 m. tons) and 177 tons (180 m. tons) of military payload, calm water range is estimated to be about 4,000 nautical miles at 20 knots. Figure 6 also shows, the effect of Sea State 5 ($H_{1/3}$ = 10 ft., 3.05 m) operation on range over the foilborne speed spectrum. It is seen that there is little range degradation in waves above foilborne speeds of 25 knots. Speed cut-offs in Figure 6 are based on power limits only:; voluntary reduction due to motions are not accounted for.

hrrangement studies for a 2,000-ton HYSWAS indicate there is volume available for at least an additional 160 tons (163 m. tons) of fuel. Results of an example range calculation with this additional fuel, and no decrease in payload, are shown in Figure 6. The HYSWAS design described is, therefore, predicted to have a range of 5,100 nautical miles at 20 knots and 2,700 nautical miles at 40 knots in calm water with a 670-ton (681 m. ton) fuel load. The additional fuel over the normal fuel load of 510 tons (518 m. tons) does not have to be replaced with ballast during burn-off. Under the maximum load condition it is estimated that, relative to calm water, take-off speed may have to be increased by several knots and the maximum speed reduced about one knot; however, nominal upper hull clearance can be maintained at somewhat higher foil loadings.

It is interesting to note (from Figure 6) that with 160 tons (163 m. tons) additional fuel, the ship has a range of 2,700 nautical miles at about 40 knots whereas the maximum speed at which this range could be achieved with only the normal fuel load is 27 knots. This makes it possible to realize a 2,700 nautical mile transit time savings of about 32 hours (or 32%) without a reduction in payload.

Overall performance (in calm water) of the 2,000-ton (7,3,0) HYSWAS with 50,000 hp (50,700 m. hp) installed and a fuel load of 670 tons (681 m. tons) is predicted to be as follows:

Maximum Speed	42 kts.
Range	5,100 n.mi. at 20 kts. 4,000 n.mi. at 25 kts. 2,700 n.mi. at 40 kts.

Endurance	255 hrs. at 20 kts. 160 hrs. at 25 kts. 67 hrs. at 40 kts.
Military Payload (M.P.L.)	177 tons (180 m. tons)
Variable Load (not incl. in M.P.L.)	58 tons (59 m. tons)

Stability, Control, and Motions

Intact Stability. Hullborne intact stability (zero speed) of the 2,000-ton HYSWAS, described earlier, has been analyzed and is presented in terms of righting arm curves for a normal weight of 2,000 tons (2,032 m. tons) and several other load conditions. The Multi-Subdivisioned Craft Hull Characteristics Program, developed at DTNSRDC, was used for these computations and results are given in Figure 7.

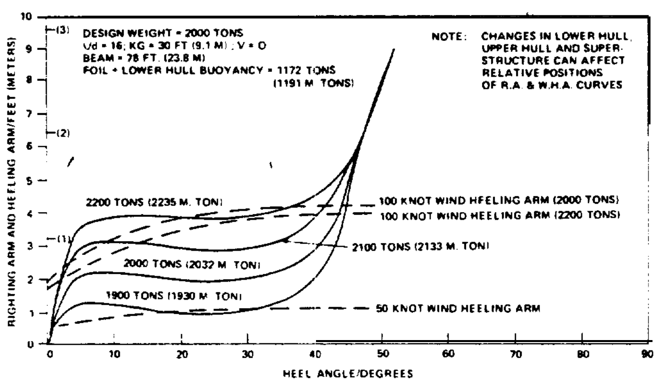

FIGURE 7 – HYSWAS HULLBORNE INTACT STABILITY CHARACTERISTICS

Heeling arm curves corresponding to beam winds of 50 and 100 knots are shown and indicate that a heel angle of about 3" can be expected from this design in beam winds of 100 knots for a 2,200-ton (2,235 m. ton) load condition. In a, 100-knot wind, ballast of about 200 tons (203 m. tons) will provide a righting arm greater than the wind heeling arm at all heel angles. It can also be seen that 100 tons (102 m. tons) of fuel could be burned off, before taking on compensating ballast, with a righting arm equal to or greater than a 50-knot wind heeling arm at all heel angles. However, as mentioned above, a conservative approach has been taken in the range computations where weight has been assumed constant with fuel burn-off below a normal fuel load of 510 tons (518 m. tons).

Numerous intact stability cases have been run. The HYSWAS concept is sensitive to upper hull beam and shape, strut height and shape, the design buoyancy/dynamic lift proportions, and center of gravity location. All of these factors must be carefully considered-in any specific HYSWAS design.

To evaluate the adequacy of intact stability of this 2,000-ton HYSWAS, the standard wind heeling criteria for U.S. Navy monohulls(7) have been applied. The projected sail area of HYSWAS in a beam wind increases with heel angle up to about 35°, after which the wind heeling moment tends tc decrease. A wind heeling arm curve, much more severe than that stipulated in the criteria, is obtained. However, HTSWAS is believed capable of meeting the righting arm wind heel crossover and energy absorption criteria for monohulls.

Foilborne Roll Control. At foilborne speeds HYSWAS designs require an automatic foil control system primarily to achieve roll stability. The Multi-Subdivisioned Craft Hull Characteristics Program was used to compute the rolling moments of the lower hull and strut at various heel angles and upper hull clearances. A quasi-static roll analysis can be performed wherein the foil roll moment at various speeds is computed and compared to the buoyant rolling moment. Righting arm plots, for foil loadings of 600 psf (2,929 kg/m*) and 1,200 psf (5,859 kg/m^2) are shown in Figures 8 and 9; other foil loading conditions are explored in Reference 4.

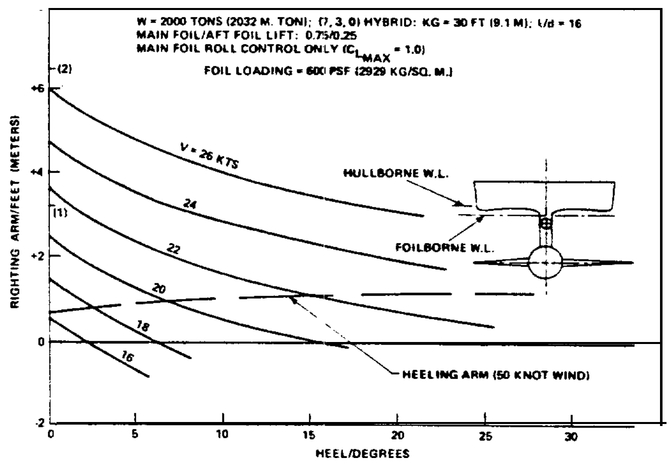

FIGURE 8 – HYSWAS FOILBORNE RIGHTING ARM CHARACTERISTICS; FOIL LOADING, = BOO PSF (2929 KG/SO. M)

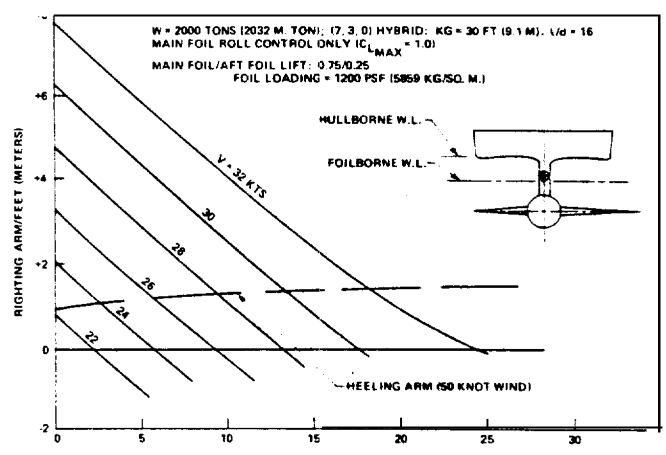

FIGURE 9 – HYSWAS FOILBORNE RIGHTING ARM CHARACTERISTICS; FOIL LOADING = 1200 PSF (5859 KG/SQ M)

These plots indicate the righting arm values available from the main foil at various combinations of speed and heel angle. Figure 10 shows the relationship of this 2,000-ton HYSWAS speed, upper hull clearance. (distance between waterline and bottom of upper hull), and foil loading to provide a given upper hull clearance. Two types of limit lines or boundaries are shown: one type represents initial chine contact; the other type consists of control limits based on wind heeling at a wind velocity of 50 knots and the ship heeled 5" as an example condition. Ship operation should therefore'be maintained at such speeds and upper hull clearances (or foil loading) that fall above the chine contact boundary and above the wind heel line. Figure 10 also shows two operating lines. The lower of the two operating lines represents the speeds and upper hull clearances as the ship transitions from hullborne to foilborne in the calm water condition. A foil loading of 420 psf (2,050 kg/m^2) corresponds to the point, or speed of about 13 knots, at which the

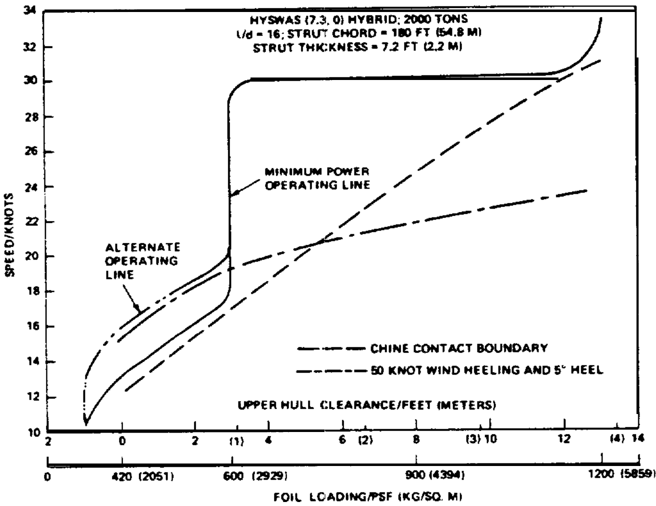

FIGURE 10 - HYSWAS OPERATING ENVELOPE

upper hull clears the water. Speed would continue to be increased to about 16 to 18 knots at a foil loading of 600 psf (2,929 kg/m^2). Power requirements are minimized if a foil loading of 600 psf (2,929 kg/m^2) is maintained as speed is increased to about 30 knots[4]. Therefore, the operating line is vertical from 18 to 30 knots followed by a transition to the design foil loading of 1,200 psf (5,859 kg/m^2) if greater speeds are anticipated or greater upper hull clearances are desired. The operation is continuous, reversible, and requires no large power changes. The upper (alternate) example operating line corresponds to a condition with a SO-knot wind on the beam and the ship heeled 5". Here, "take-off" is at about 17 knots and a foilborne speed of 20 knots (or greater) would have to be maintained at 600 psf (2,929 kg/m^2) foil loading to remain above the 50-knot wind heel boundary.

A conservative approach was adopted in the foilborne roll control analysis discussed above. The quasi-static analysis assumes that the foil automatic control system is not sensitive to heel angles, and, therefore, control changes are made at the instant a given heel angle is attained. Using state-of-the-art automatic control systems for hydrofoils, it is anticipated that roll angles can be held within about 5" on HYSWAS when foilborne.

Although criteria for the evaluation of HYSWAS take-off characteristics have not yet been established, a preliminary analysis indicates that HYSWAS has sufficient roll control at low speeds to maintain stability when combined with the ship's intact stability. The effect of head seas on take-off performance is of concern and is being investigated. It is not clear that this is a critical problem, but experiments are planned to clarify this issue.

Foilborne Stability and Motions. From experimental evidence on SWATH ship models, it was suspected that the long slender hull of the HYSWAS form could have a speed-dependent instability in pitch.[8] An investigation(") was therefore made to determine the desirable foil size and location of this 2,000-ton HYSWAS design to provide suitable vertical-plane stability. Although the foil system could have an automatic pitch/heave control capability, the analysis was made with foils in the passive mode (controls fixed). Reference 9 also included, for the final foil configuration selected, ship motion in regular head seas and the probable range of the rate of foil deflections for the control of heave and pitch if desired. A conventional (airplane-type) foil arrangement, as shown in Figure 2, with 75% of the lift on the main (forward) foil and 25% on the secondary (aft) foil is recommended. This is estimated to provide positive vertical-plane stability through a speed of 50 knots (to ensure that the ship's maximum operational speed is included) with the control system in a passive mode. Automatic foil control sensitive to pitch/heave motions is predicted to enhance the stability characteristics of HYSWAS, and, therefore, would probably be incorporated into a HYSWAS design. Although a detailed evaluation of this option has not yet been undertaken, analysis to date shows that foil control surface deflection rates are practical in high, steep waves.[9]

Analytical results show little effect of speed on the optimum locations of the main foil when ship speeds exceed 30 knots. Also, changes in HYSWAS's longitudinal center of gravity location within several feet from the normal full load position are expected to have a relatively small effect on vertical-plane stability.

Details of the stability and motion analysis for regular waves are given in Reference 9; highlights of motion results are shown in Figures 11 and 12. Here, heave and relative vertical motion for the 2,000-ton design are plotted against wave length/ship length ratios for speeds of 30 and 40 knots. The analysis predicts, for example, that in a regular head wave 1,800 feet (549 m) long with an amplitude of 20 feet (6.1 m) (as may be found in the Pacific Ocean), the lower hull of the 2,000-

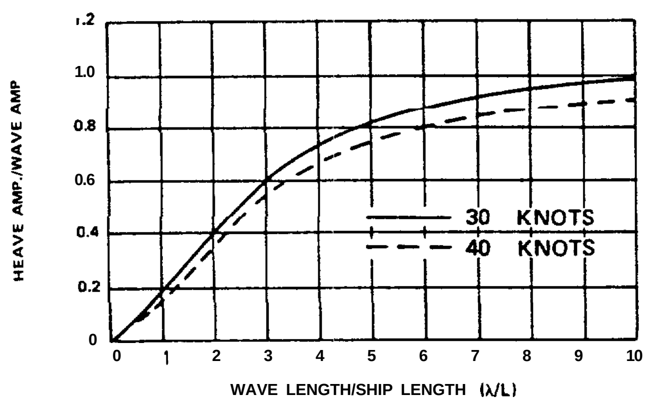

FIGURE 11 - 2000-TON HYSWAS HEAVE MOTION IN REGULAR HEAD WAVES WITH CONTROLS FIXED

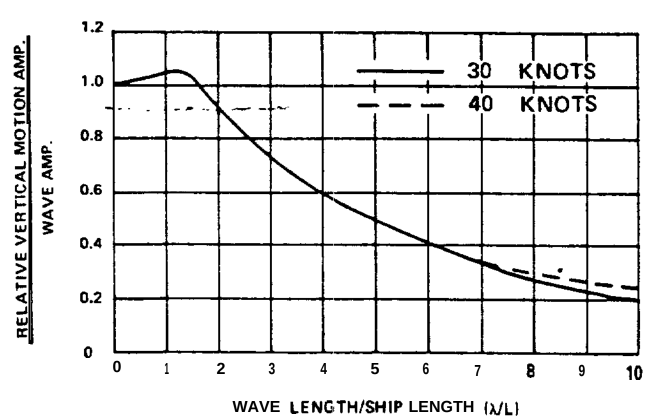

FIGURE 12 - 2000-TON HYSWAS RELATIVE VERTICAL MOTION OF FORWARD END OF STRUT IN REGULAR HEAO WAVES WITH CONTROLS FIXED

ton HYSWAS will not broach the free surface and neither will the bottom of the upper hull be subjected to wave contact. The relative vertical motion characteristic curve (Figure 12) also indicates that for a regular wave of about 200 feet (61 m) in length and 7.5 feet (2.3 m) amplitude (15 feet (4.6 m) crest to trough, which is equivalent to a mid-Sea State 6, based on significant wave height), the top of the lower hull would barely break the surface, and the vertical motion at the forward end of the strut is less than the upper hull clearance. The corresponding vertical acceleration at the ship center of gravity for the latter case is estimated, from the predictions of Reference 9, to be about 0.10 g which is well within the human tolerance level. Because of these characteristics, HYSWAS when foilborne is predicted to have both heave and pitch motions superior to conventional monohulls in head waves and hence a potential for good seakeeping.

Maneuvering

No detailed analytical investigations or tests have been made on turning characteristics and rudder configurations for HYSWAS designs. However, hydrofoil and Small Waterplane Area Twin Hull (SWATH) ship[10] experience is expected to provide guidance for future HYSWAS maneuvering studies.

The foil system of HYSWAS is expected to aid in turning since the ship should be able to bank into a turn. Although a final selection of a rudder configuration has not been made, a surface piercing strut rudder would be preferred for HYSWAS from the point of view of rudder control machinery installation. This equipment would be in the upper hull where space is readily available. Also a strut rudder allows a high degree of design flexibility in rudder chord selection without an overall ship weight penalty. A balanced rudder design is preferred to minimize machinery weight, and has been assumed in the weight analysis. Possible rudder force reversal can be avoided with a balanced design by introducing a cut-out (or gap) of between 0.30 and 0.40 of the rudder chord in the strut.[11] It is planned to include this feature in early model tests to determine rudder effectiveness and impact on drag.

Structures

The Structural Synthesis Design Program (SSDP)[12] was used to study the primary structural weight of HYSWAS as Phase I of an effort to develop a semi-automatic structural weight estimation routine for hybrid ships. Figure 13 shows the HYSWAS structural arrangement used in this program.

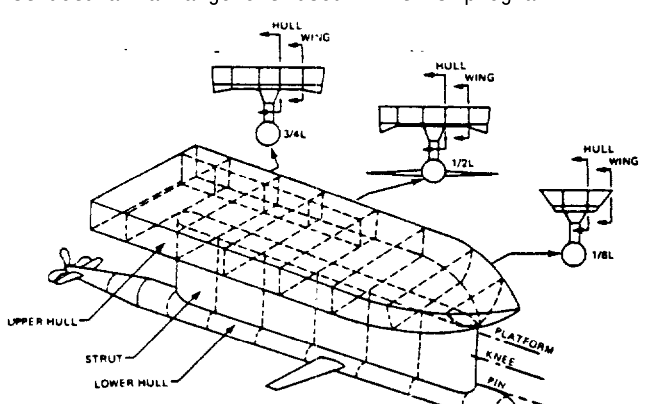

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FIGURE 13 -STRUCTURAL. ARRANGEMENT OF HYSWAS

A 2,000-ton HYSWAS designed with a steel lower hull and strut and aluminum upper hull was designated the "control" ship. Bending moments and materials of construction were varied to study their effect on structural weight. HYSWAS differs from SWATH in that the longitudinal bending moment is more severe than the transverse moment. SWATH experience and preliminary calculations produced a reference longitudinal bending moment of 12,000 foot-tons (3,716 m-m. tons) for this 2,000-ton HYSWAS design. Several multiples of this value were then used as shown in Figure 14. It was

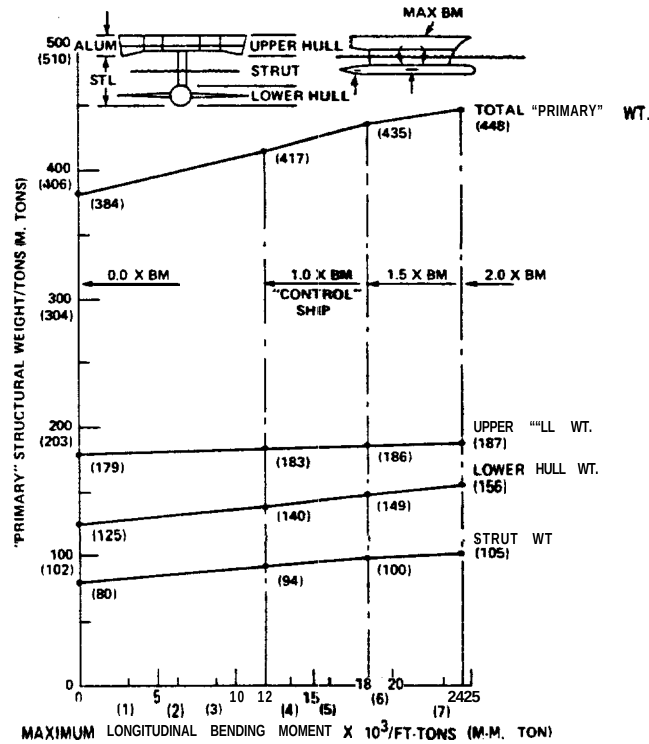

FIGURE 14 - "PRIMARY" STRUCTURAL WEIGHT VERSUS MAXIMUM LONGITUDINAL BENDING MOMENTS (12)

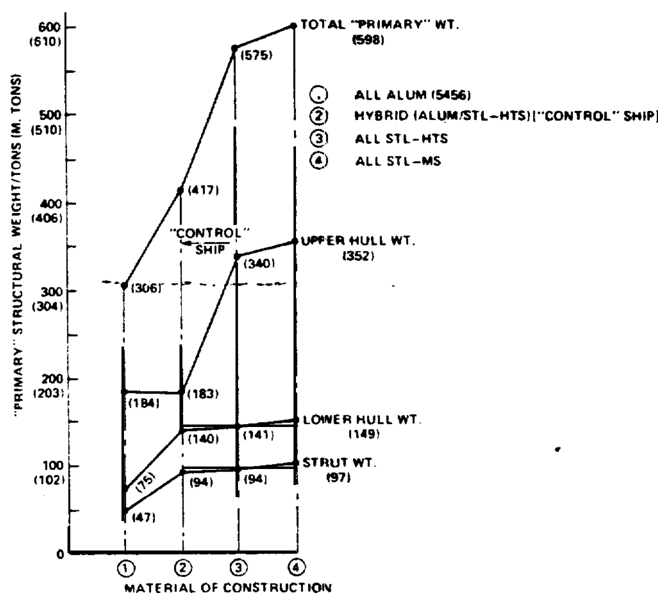

FIGURE 15 - "PRIMARY" STRUCTURAL WEIGHT VERSUS MATERIAL OF CONSTRUCTION (12)

found that the primary structural weight is relatively insensitive to bending moment: local loads such as hydrostatic and deck loads, dictate the weight. Figure 15 shows how various materials were used in the design; the all-aluminum ship shows large weight savings, compared to the "control" ship. The all-steel designs show little weight variation, however all are heavier than the *"control"* ship.

From preliminary results, HYSWAS in the 3,000- to 4,000-ton (3,048 to 4,064 m. tons) size range appear to be candidates for steel-aluminum structures; however, those in the 1,000- to 2,000-ton (1,016 to 2,032 m. tons) range require all-aluminum designs. Therefore, to minimize weight, the 2,000-ton HYSWAS described in this paper is designed with an all-aluminum structure. Secondary structure, such as doors, hatches, and welding, etc., was taken at 25% of &he primary structure. Based on similar superstructures,(13) a conservative superstructure structural weight density of 1.0 lb/ft^3 (16 kg/m^3) is used.

The SSDP was also applied to obtain an estimate of the foil weight. Since this was only an approximation, no torsional analysis was included. The foils were HY-100 throughout; foil weights and dimensions and carry-through structural weights are given in Figure 16 from Reference 12.

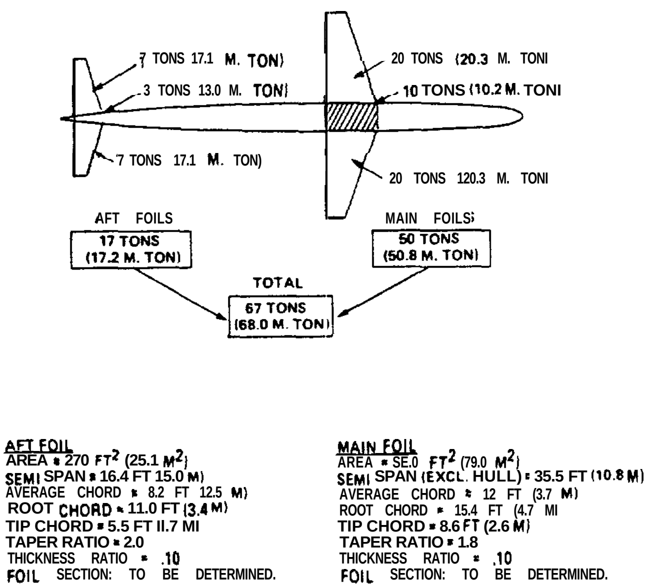

FIGURE 16 - FOIL GEOMETRY AND WEIGHTS OF A 2000.TON HYSWAS (12)
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Some critical areas need to be investigated, including the lower hull-strut and strut-upper hull intersections. It is emphasized that proper design for structural weight minimization and fatigue in these locations is important to the HYSWAS configuration.

Propulsion Systems

Early *in* the analysis, aircraft-derivative gas turbines were selected as the prime mover due to their light weight and compactness. A contra-rotating propeller was preferred because of the high propulsive coefficient (P.C.) as shown in Figure 5, and reduction of the rolling moment caused by the torque of a single screw.

Arrangements with engines in the lower hull were investigated. It was found, however, that locating the engines in the upper hull is preferred because of better arrangements and lower overall center of gravity, even though the ship weight is larger. Simply stated, this is due to a tradeoff of fuel and engine locations. This is expected to be true for all HYSWAS unless a higher power lightweight engine (sufficient to provide the total propulsion power) becomes available.

One propulsion system arrangement investigated requires a Z-Drive. Power is transmitted from each of the two engines through a series of bevel and planetary gears and shafts, illustrated in Figure 17, to fixed pitch contrarotating propellers.

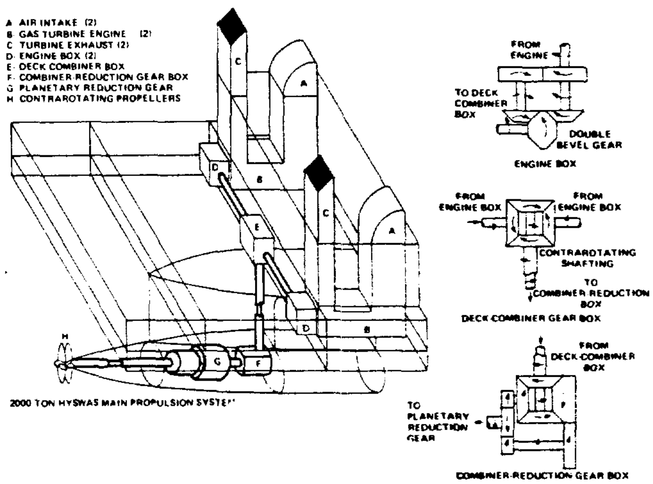

FIGURE 17 SCHEMATIC OF MAIN PROPULSION SYSTEM AND MAJOR TRANSMISSION COMPONENTS

Three engine options were examined: standard LM 2500, supercharged LM 2500, and FT-9.

The current LM 2500 engine is rated at 22,500 BHP (22,800 m. hp) (maximum continuous at 80°F (27°C)); 25,000 BHP (25,350 m. hp) (maximum continuous) is anticipated. 'This provides 50,000 SHP (50,700 m. hp) total, adequate for about 42 knots for this design.

The FT-9 is expected to have a 33,000 BHP (33,462 m. hp) (maximum continuous at 100°F (38°C)) rating. It is four inches longer than the LM 2500, fits in the designed engine room, but weighs 3,500 pounds (1,588 kg) more (per engine) than the LM 2500.

The LM 2500 supercharger(14) is expected to boost the engine power to 32,000 BHP (32,448 m. hp) (maximum continuous at 80°F (27°C)). It weighs about 9,000 pounds (4,082 kg) and lengthens the unit by about 12 feet (3.7 m). This would require major rearrangement of the upper hull.

The standard LM 2500 engine was chosen. If higher power is desired, the FT-9 would be preferred.

The two designated LM 2500 engines with their auxiliaries, enclosures, and mounts weigh 39.7 tons. They provide 50,000 SHP; however, *the* transmission system and propellers are sized for 60,000 SHP so that higher power could be accommodated at a later date.

The engine box (see Figure 17) is based on a unit intended for possible use on a 750-ton (762 m. ton) Developmental Big Hydrofoil (DBH). It takes power from the engine through a right angle double bevel gear (double mesh) unit to horizontal deck shafting.

The iwo deck shafts transmit power to the deck-combiner box which is a quadruple mesh bevel gear unit. The DBH shoulder box weight was used as a basis for weight estimation. From this deck-combiner box, power is transmitted through vertical coaxial contrarotating shafting to the lower hull.

The combiner-reduction gear box,[15] located in the lower hull, takes power from the vertical shafts, recombines it, reduces shaft speed by a ratio of 1.625 to 1 and transmits power aft.

A contrarotating planetary reduction gear reduces the speed and transmits the power to contrarotating propellers. An appropriate gear would be similar to the MARAD/Curtiss-Wright System F. The current System F has an estimated dry weight of 177,200 pounds (80,377 kg). It is understood that for the required rpm. torque and thrust of a 2,000-ton HYSWAS, a modified version capable of transmitting about 60,000 hp at 270 rpm, would weigh about 70,000 pounds (31,751 kg)*. The weight reduction would be in the gears, thrust bearing, and upper casing. However, the current System F, illustrated in Figure 18, could be used on a developmental ship to reduce rework and cost. It has a speed reduction of 8.18:1 and an expected efficiency of 99.1%.

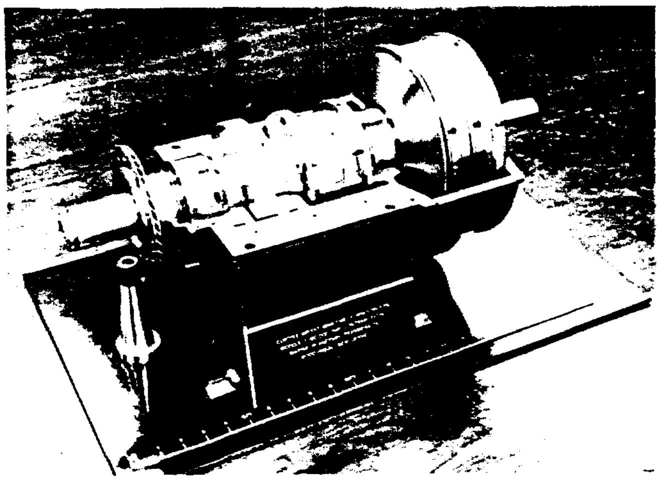

FIGURE 18 CONTRAROTATING MARINE PLANETARY TRANSMISSION

Gear boxes have an estimated weight of 97.000 pounds (44,000 kg). Shafting weight is estimated at 13,900 pounds (6,300 kg) of which 9,215 pounds (4,170 kg) is propeller shafting. Further details can be found in Reference 16.

Power is transmitted to the water through a set of concentric contrarotating propellers. Although the design of the contrarotating reduction gear dictates that the speed, torque, and power cannot be the same for both screws, they are assumed the same in the design of an equivalent propeller, which is projected for 30,000 SHP (30,420 m. hp). The equivalent propeller has the following characteristics:

Ship Speed, V = 42.5 knots
Delivered Horsepower, DHP (per propeller) - 28,500 (28,900 m. hp)
Thrust Deduction, t = 3.5%
Wake Fraction, w = 7%
Thrust = 141,000 pounds (64.000 kg)
Troost B4.55 Equivalent Propeller - 270 rpm optimum
Diameter, D = 13.02 feet (3.97 m)
Pitch/Diameter - 1.35
Open Water Efficiency, η_0 = 0.77
Relative Rotative Efficiency, η_R = 0.95
Hull Efficiency, η_H = 1.03
Mechanical Efficiency, η_M = 0.95
Propulsive Coefficient (including η_M), P.C. = 0.716

Values of t, w, η_R, and η_H were taken from the SWATH III demi-hull model tests.[17] A more exact estimate would be necessary for an actual design. Propulsive coefficients for speeds from 15 knots to 45 knots were calculated. An efficiency of 5% was added to the P.C. due to the beneficial effects of contrarotation, as suggested by Hadler.[18] This efficiency increase may not be realizable at high speeds, so it was reduced beyond 40 knots. The resultant P.C. curve is shown in Figure 5.

The largest known marine contrarotating propeller installation to date, according to *Jane's Fighting Ships*,[19] is the 15,000 SHP (15,210 m. hp) (total) submarine U.S.S. JACK. Since this HYSWAS design is much larger, several factors should be examined: shaft bearings and seals for these high powers and speeds could pose a problem, lubrication could be difficult, and potential vibration problems should be determined.

Diesel and gas turbine auxiliary engines were examined. It was estimated that 1,000 SHP (1,014 m. hp) for each of two engines would provide a speed of about eight knots hullborne. Since upper hull weights are critical, gas turbines are preferred as auxiliary engines despite their higher fuel rate. Each engine would drive through one or two rotatable retractable thrusters located at the outboard extremes of the upper hull. This should give good low speed maneuverability. The retracted thrusters would produce no drag and are not vulnerable to damage when the ship is foilborne.

Two major HYSWAS machinery considerations remain. Due to the critical nature of HYSWAS weight and center of gravity, it is believed that water screws are the most suitable means of propelling the ship. Although materials and construction of gearing, shafting, and bearings for Z-Drives would have to be improved for HYSWAS, no breakthroughs are required. Depending on the limitations, weight, and reliability of advanced electric systems, these could also be transmission candidates. As shown above, the higher propulsive coefficient of contrarotating propellers improves HYSWAS performance and would probably be selected for all large HYSWAS. It should be pointed out, however, that although this would solve the torque problem, HYSWAS is not competely dependent upon a contrarotating propulsion system since a single screw or side-by-side propellers may also be feasible.

Ship System Engineering

It is not sufficient that a hydrodynamic form be generated and its performance estimated. It must be shown that this form is capable of performing a mission and, when configured to the mission, that it is consistent with the assumptions used in generating the performance figures. An AAW/ASW/SUW mission similar to a SWATH escort[13] was chosen and was the basis for choice of manning and the weapons suite. While certain weapons are specified, a high degree of flexibility in weapons choice is possible. In addition, the ship has the capability of launching, retrieving, and hangaring two LAMPS-type helicopters. The HYSWAS's deeply submerged streamlined lower hull is anticipated to be good for bow-mounted sonar. Figure 19 shows several views of this configuration.

*Conversations with D. Falenta, Curtiss-Wright, 21 August 1975; D. Falenta and E. Critelli, MARAD, 4 September 1975.

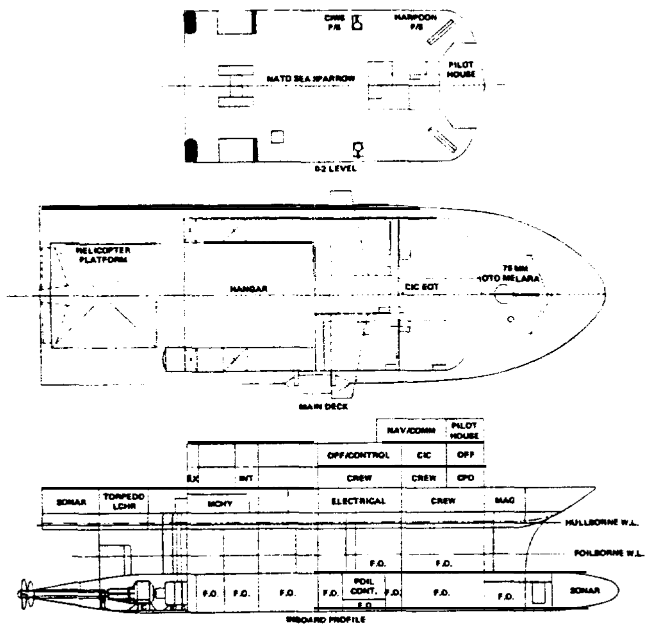

FIGURE 19 - 2000-TON HYSWAS COMBATANT ARRANGEMENT

Weights were derived from SWATH ship and hydrofoil practice. However, weights comparable to monohull practice were used when design features were similar.

Fuel tanks in the lower hull have capacity for the required 510 tons (518 m. tons) of fuel. By filling all the tanks in the lower hull and strut, 160 tons (163 m. tons) of additional fuel can be accommodated. This moves the center of gravity down by 0.7 feet (0.2 m) and forward by 2.5 feet (0.8 m). The fuel storage positions must be carefully established for each HYSWAS to keep the center of gravity in a satisfactory region. For this design, the availability of sufficient volume for all fuel does not appear to be a problem.

The ship is *arranged* to provide functional accessibility, particularly among combat control areas. Compartment deck areas are specified to be similar to those on a chosen 2,000-ton SWATH escort, except in those locations where the SWATH ship area allocation appeared to be excessive.

Living and dining spaces were allocated to be comparable to modern Navy practice. Table 3 compares the manning estimates and approximate areas for the 2,000-ton HYSWAS to those for other ships.

TABLE 3
MANNING ESTIMATE AND
ARRANGEMENT AREA

MANNING ESTIMATE	DBH	PG-84	DE-1037	HYSWAS 2,000
Officers	5	4	9	12
CPO's	5	4	9	12
Enlisted Men	36	21	171	94
TOTAL	46	29	189	118
AREA/CREW MAN (FT²/MAN)	**DBH**	**PG-84**	**DE.1037**	**HYSWAS 2,000**
Officer Berthing	78.0	64.8	112.0	72.0
CPO Berthing	42.0	46.0	31.0	39.0
EM Berthing	20.7	24.3	17.1	37.0
Wardroom/Mess Room & Lounge	41.0	31.3	38.6	32.5
CPO Mess Room & Lounge	39.0	- -	18.6	16.5
Crew Mess Room	8.3	6.2	4.9	10.8

The following are approximate enclosed volumes for the components:

Components	Volume (ft3)	Volume (m^3)
Lower Hull	42,500	1,203
Strut	21,200	600
Upper Hull	168,000	4,757
Superstructure	146,500	4,148
TOTAL	378,200	10,708

The volume available for crew and operation spaces is more than adequate, so it appears that WSWAS is not volume limited.

A more detailed breakdown was estimated for each weight group. Structural weights were based on the results from Reference 12. A double bottom is included in the upper hull of the HYSWAS design, and, due to the shape of the upper hull bottom, there is much volume which is unused except for pipe or wire ways. As this results in a higher structural weight, perhaps some means of reducing this penalty can be found, but this must await further examination of structural impact loads in waves.

Propulsion system weights were estimated from individual components. Electric plant weights were based on NAVSEC SWATH ship designs[13] and hydrofoil estimates.[20] Communication and control weights were taken from a 2,000-ton SWATH escort, with some modification. The auxiliary weights were derived from SWATH advanced system and hydrofoil practice. Outfit and furnishings weights are slightly lighterthan conventional SWATH system weights because of anticipated use of a certain degree of lightweight systems. The weapons (mentioned earlier in the description) are the same as for a 2,000-ton SWATH escort. Figures 20, 21, and 22 show electric plant, auxiliary, and outfit and furnishings weights respectively as functions of various ship parameters.

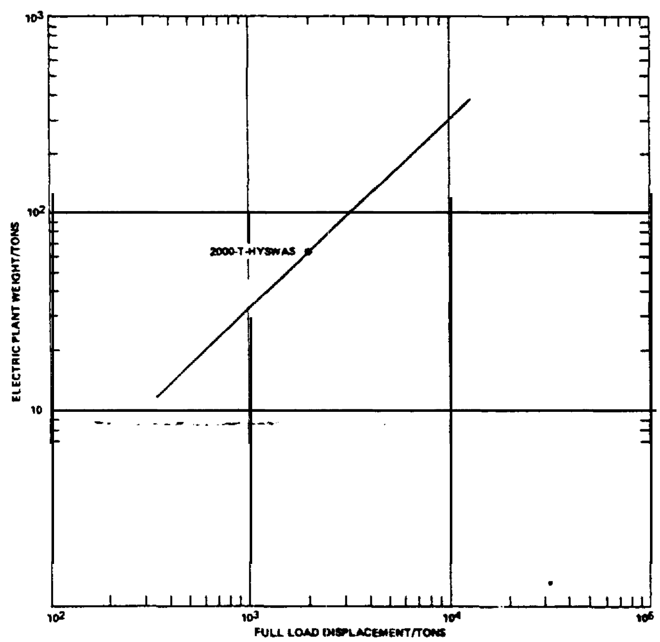

FIGURE 20 - ELECTRIC PLANT (GROUP 300) WEIGHT TREND

These curves reflect monohull, SWATH Ship and hydrofoil experience. The curves shown were used to check the group weights derived from a detailed analysis and were found to be in agreement.

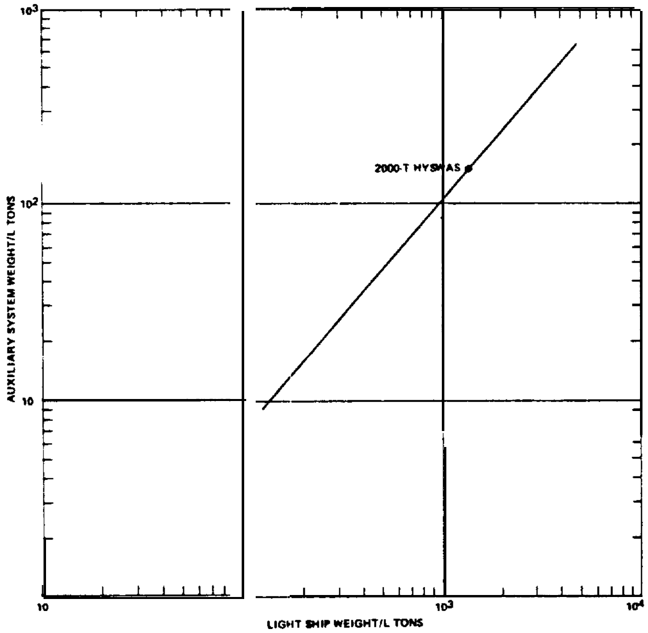

FIGURE 21 -AUXILIARY SYSTEMS (LESS FOIL/STRUT). GROUP 500 WEIGHT TREND.

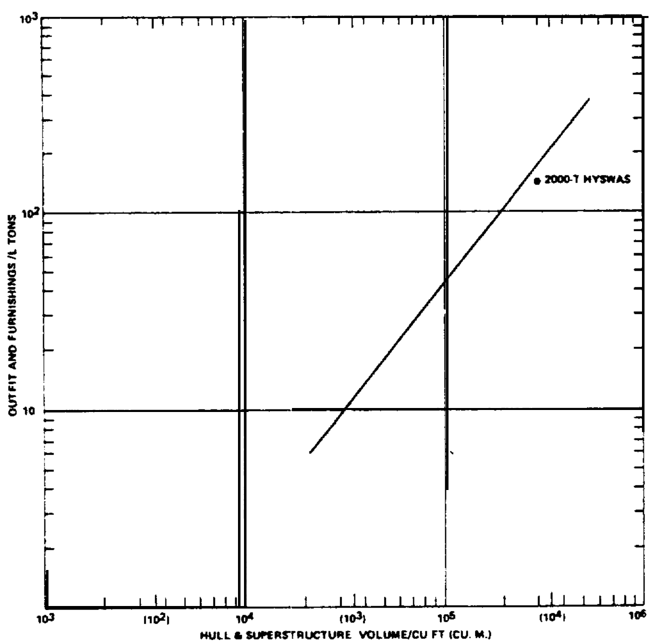

FIGURE 22 - OUTFIT AND FURNISHINGS (GROUP 600) WEIGHT TREND

Variable loads estimates were derived from SWATH and hydrofoil practice and independent analyses. Further details on the group weights and a three-digit breakdown can be found in Reference 16. A one-digit weight summary is given in Table 2.

It was necessary to use some advanced technology subsystems to keep their weight to a minimum. In this concept, as with many other advanced ships, the actual figures in many weight groups are dependent, to a great degree, on the amount that one is willing to pay for advanced technology. The cost of concepts which depend for their viability upon lightweight systems will be high; this cost cannot be avoided.

This 2,000-ton HYSWAS combatant has a center of gravity 30.5 feet (9.3 m) above the baseline and 129.7 feet (39.5 m) aft of the lower hull bow. The vertical and longitudinal locations of the center of gravity are very important. A low center of gravity aids in providing sufficient hullborne stability and reduces the amount of roll control that must be supplied by the foils when the ship is foilborne. The vessel center of sustention (combination of buoyant and dynamic forces) must be located in a vertical line with the ship center of gravity. To provide sufficient quasi-static and vertical plane stability, there is a region of permissible longitudinal positions of the center of gravity as mentioned in the hydrodynamics section. The center of gravity location of this 2,000-ton HYSWAS design is appropriate for satisfactory stability in all modes.

In the absence of a detailed mission analysis, a weapons arrangement similar to a 2,090-ton SWATH escort[13] was adopted :Eor purposes of illustration. The weapons, mentioned earlier in the paper, can be accommodated.

Conclusions

A HYSWAS form combines the favorable lift-drag ratios (L/D) of a buoyant vehicle at low speeds and the relatively high L/D of a fully submerged hydrofoil dynamic lift system at moderate to high speeds to provide relatively favorable drag characteristics continuously over a broad speed spectrum. With about 70% buoyancy and 30% dynamic lift, HYSWAS can be operated in a foilborne mode at the lower end of the speed spectrum by unloading the foil and accepting a higher waterline on the strut with a marked improvement in performance below 30 knots. 'For the specific 2,000-ton (7,3,0) HYSWAS design described, "take-off" speed is about 13 knots, minimum foilborne operating speed is 16 to 18 knots, and the maximum speed is about 42 knots with 50,000 SHP (50,700 m. hp) installed. Speed degradation due to rough water is expected to be small.

A weight estimate :Eor an all-aluminum (7,3,0) 2,000-ton HYSWAS results in a military payload of 177 tons (180 m. tons) with a normal fuel load of about 510 tons (518 m. tons). This results in a predicted calm water range of about 4,000 nautical miles at a foilborne speed of 20 knots. An additional fuel load of 160 tons (163 m. tons) can be accommodated (without a reduction in payload) which increases calm water range at 20 knots to about 5,100 nautical miles, and provides a range capability of 2,700 nautical miles at about 40 knots.

The HYSWAS form requires an automatic control system. Quasi-static foilborne roll control analysis indicates adequate control down to between 16 to 18 knots in calm water; in 50 knots beam winds the minimum foilborne speed would be about 20 knots. It is predicted that the 2,000-ton HYSWAS foil system with controls fixed will maintain positive pitch and heave stability through maximum speed. Incorporating an automatic feature in the foil control system for pitch/heave control can enhance vertical-plane stability. The 2,000-ton HYSWAS design described, when foilborne, is estimated to have both heave and pitch motions superior to conventional monohulls in head seas, and hence a potential for good seakeeping.

The general arrangement of the 2,000-ton HYSWAS design provides for a complement of 118. It can carry several types of weapons and two LAMPS-type helicopters. The form appears to offer good arrangement flexibility. A fixed-pitch, contrarotating propulsor appears to offer certain advantages for the HYSWAS form; however, the design is not completely dependent on this feature since a single screw or side-by-side propeller arrangement may also be feasible.

At this early stage of development, the HYSWAS (7,3,0) hybrid form in a 2,000-ton size combines many desirable characteristics in a single platform and, therefore, appears to be a candidate for small, open-ocean, all-weather naval combatants.

Acknowledgements

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