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The SWATH Ship Concept and Its Potential

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SMALL WATERPLANE AREA TWIN HULL (SWATH) SHIP CONCEPT AND ITS POTENTIAL

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Abstract

The SWATH concept is described, variations and design trade-offs are discussed, and the potential performance is analyzed. Results of tests on models and on the 217-ton prototype SSP KAIMALINO are presented. Future applications are discussed. The advantages of SWATH ships over conventional monohulls vary depending upon the application, but in general they are: greatly reduced motion in waves, both underway and at rest; larger deck area and internal volume; and reduced drag in the higher sea states.

Introduction

The need exists for ships having reduced motion in large waves so that speed can be maintained and men and equipment can continue operating. In many cases, the need also exists for more deck area and internal volume. The Small Waterplane Area Twin Hull (SWATH) ship can satisfy these needs. An ocean-going version, the SSP KAIMALINO, is shown in figure 1 and is based upon a new type of semisubmerged ship concept.[1-3]

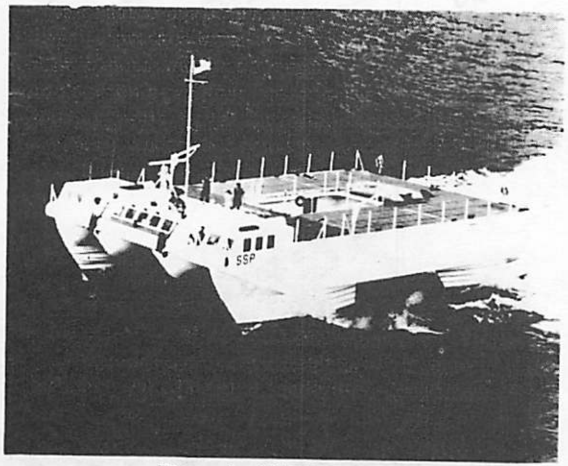

Figure 1. SSP KAIMALINO.

Because of the small waterplane area on a SWATH ship, passing waves produce only a fraction of the buoyancy change experienced by a conventional monohull, resulting in significantly less motion. Also, whatever motion does occur can be further reduced when the SWATH ship is underway by the use of active fin control, since the small waterplane area makes possible near-full control over heave, pitch, and roll. Furthermore, since the draft is greater than that of a monohull, and the flow into the propellers is more uniform, there is a tendency toward less propeller cavitation and quieter, more efficient propeller operation. Even when the SWATH ship is at rest, the small waterplane area – combined with the dispersed configuration, the twin torpedo-like lower hulls, and fin appendages – produces much less motion in waves than a monohull.

This paper is written primarily from the viewpoint of the Navy, so emphasis is placed on naval operations. From the naval-mission viewpoint, the SWATH ship concept can be potentially employed to increase the effectiveness of a mix of small, lower-cost, lower target-value ships which enhances operational flexibility. Thus, given a set of various kinds and sizes of small SWATH ships, a wide variety of missions could be satisfied by using different mixes of the individual ships.

Perhaps the greatest asset of a SWATH is its ability to carry modern aircraft and missiles, which are now developed to the point at which small ships can be given considerable firepower and air capability. SWATH would permit the operation of V/STOL aircraft, helicopters, and missiles from unusually small naval craft. Men and equipment could remain functional in high sea states, and motion-induced fatigue minimized.

The many advantages of SWATH ships relative to monohulls must be traded off against the possible disadvantages of their sometimes-greater structural weight and cost, generally greater beam and draft, higher calm-water drag at low-to-moderate speeds, and sensitivity to unanticipated weight growth and load changes. Some of these disadvantages can be reduced by relatively simple means. For example, the deep draft of large SWATH ships (over 20,000 tons) can be substantially reduced by offloading fuel and payload in deeper water.

Typical design speeds of SWATH ships could range up to 35–40 knots for gas turbine operations, and to 15–25 knots for diesels. Present nuclear power would probably be limited to large versions because of greater weight and cost. A 500-ton size with gas turbines appears acceptable for ranges up to around 1,500 miles; 2,000-ton sizes and up would provide global operations with ranges of 3,000 miles and up.

Background

The basic small-waterplane-area, twin-hull ship concept dates back to at least the 1905 patent by Nelson shown in figure 2, and possibly earlier. Other early patents by Faust (1932), Creed (1946), and Leopold[4] (1967) are shown in figures 3, 4, and 5. These earlier designs would provide acceptable performance at low to moderate Froude numbers, but would tend to become dynamically unstable at moderate to high Froude numbers or design speeds. A solution to this problem was developed by Lang (1971), figure 6, through a combination of SWATH-like components, with the addition of fins for stability. This new design approach was developed during the 1950's and 1960's and later introduced to the Navy in 1968 at the Naval Ocean Systems Center** (NOSC), thus representing the first Navy-sponsored work on SWATH.[3]

Cousins of the SWATH are the numerous offshore oil drilling rigs, figure 7. Although many types of these have twin hulls, a small waterplane area, and propulsion, they are not SWATHs in the Navy sense since they are not designed for moderate and high speeds, and are limited in speed to several knots. Another cousin of the naval SWATH is the DUPLUS,[5] figure 8, which

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*Head, Advanced Concepts Division, Fleet Engineering Department, Member AIAA and SNAME
**Called the Naval Ordnance Test Station at that time

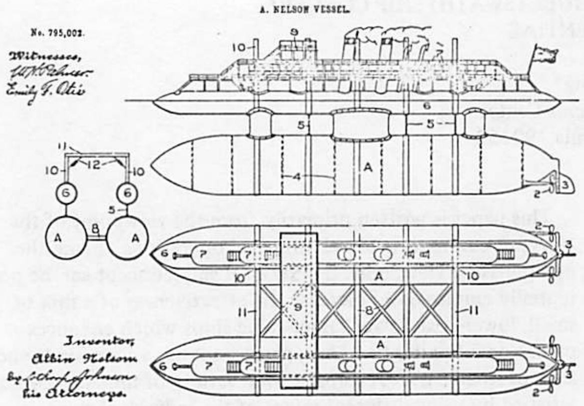

Figure 2. NELSON – 1905.

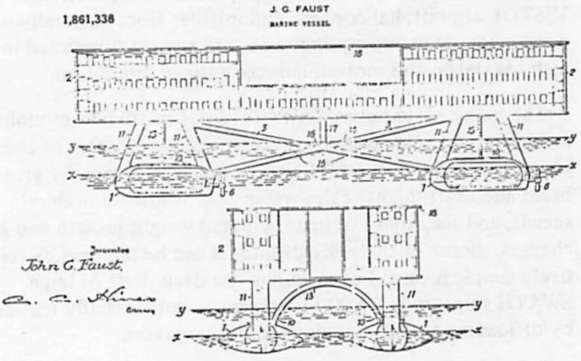

Figure 3. FAUST – 1932.

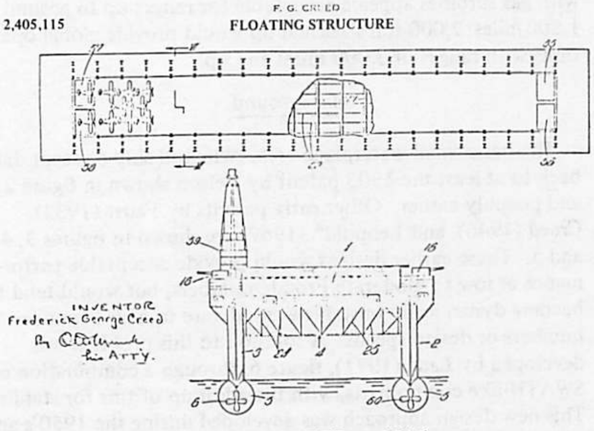

Figure 4. CREED – 1946.

was built in the Netherlands and has a medium, rather than small, waterplane area and is designed for an 8-knot top speed. This version was invented by Stenger and has two large horizontal hydrofoils spanning the two lower hulls, one at the front and one at the rear. Considerable interest in SWATH has also been shown in other countries, including Sweden[6] and Japan.

Since 1969, considerable research and design work has been done at the David Taylor Naval Ship Research and Development Center (DTNSRDC), Naval Ship Engineering Center

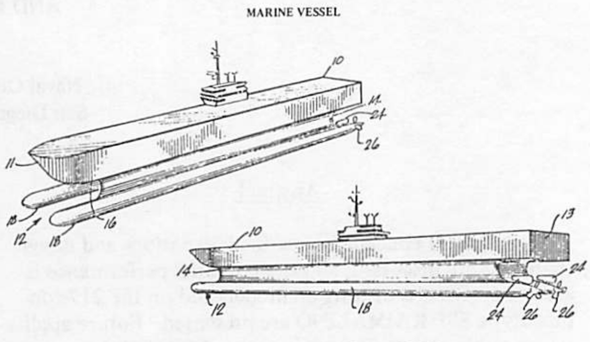

Figure 5. LEOPOLD – 1967.

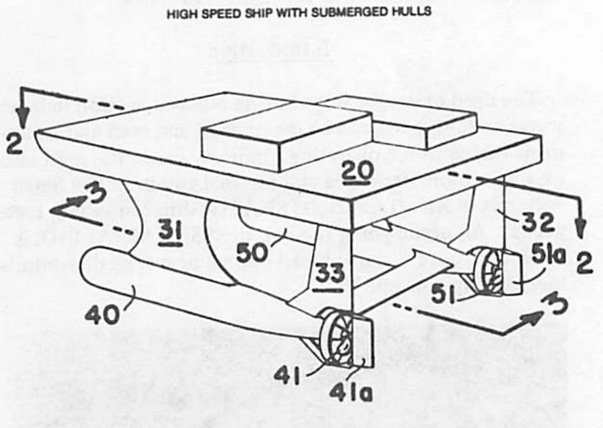

Figure 6. LANG – 1971.

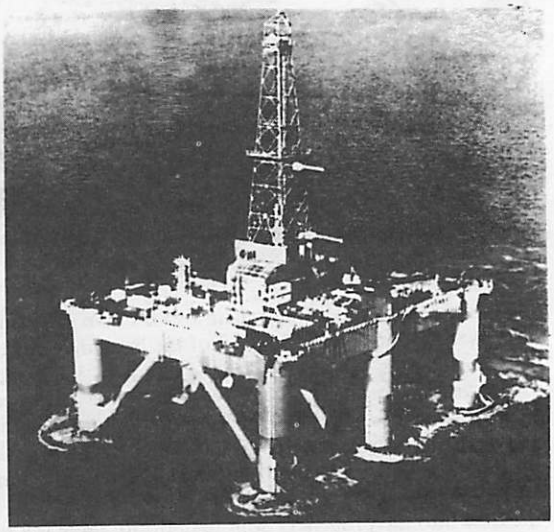

Figure 7. Offshore drilling rig.

(NAVSEC), and NOSC. Also, SWATH work has been conducted at various universities[7], private companies, and the Maritime Administration (MARAD). The only large ocean-going version of a SWATH is the SSP KAIMALINO pictured in figure 1, and referred to herein as the SSP, which stands for Stable Semisubmerged Platform.[8,9]

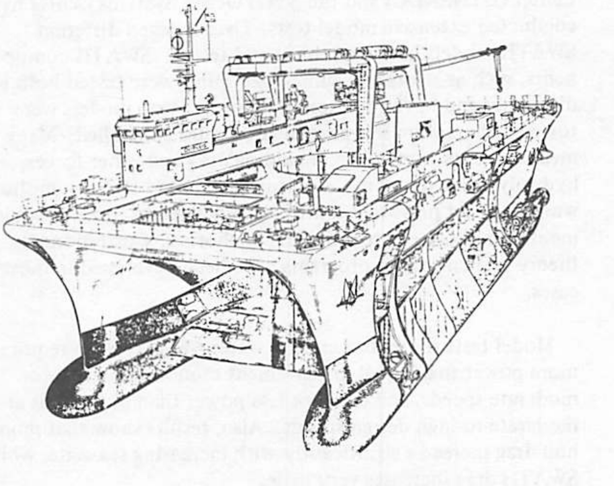

Figure 8. Netherlands DUPLUS.

Prior to the Navy's SWATH program, the need for a low-motion range support craft arose at the Naval Undersea Center. Consequently, the design of the SSP began in 1970, under the sponsorship of the Director of Naval Laboratories.* In 1972 at the Curtis Bay, Maryland, Coast Guard Shipyard, construction began. The lower hulls and struts were made of steel, and the cross structure was aluminum. Construction was completed the next year and the SSP reached its design speed of 25 knots in November 1973. In January of 1975 the SSP was transported to the NOSC** Hawaii Laboratory, where it has since been used as a range support craft.

Sea tests were conducted in July and August 1975 as part of the DTNSRDC-Navy SWATH trials. The excellent stability and maneuverability were verified. The results correlated well with theory and model tests. Even at rest or at low speed in large waves, there was little motion because of its small waterplane area, large natural periods, and good damping.

An automatic control system was installed in September 1975, and the already small motions were further reduced. In December 1975 the SSP began its mission as a range support craft. Its first range support task consisted of tests on a new expendable sound source that were conducted off the island of Kauai.

In 1976 sideward hull extensions were added to the SSP to increase the fuel and payload capability to 50 tons. The displacement was increased from 190 long tons to 217. Also, a 6-inch-thick acrylic dome was placed at one bow for underwater viewing; as a result, the SSP also offers great promise for unique marine biological studies such as dolphin research, shark and fish behavior, and bioacoustics.

The recent addition of a deck cover for the well permits helicopter operations. Over 80 landings and take-offs were made in sea states up through sea state 4 by Navy SH-2F, LAMPS helicopters, weighing 12,800 pounds (figure 9). SWATH ships make excellent air support craft. With automatic controls, the SSP experienced a near-level ride in sea state 4, which scales to approximately sea state 6 for destroyer-size versions. Landings were also made by an HH-52 Coast Guard helicopter.

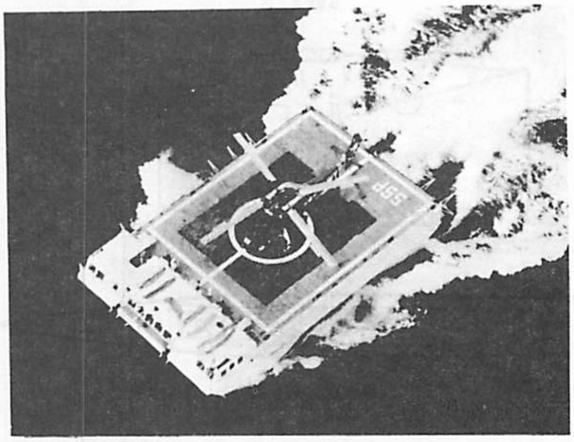

Figure 9. SSP helicopter trials.

Most of the research on SWATH has been sponsored by NAVSEA. Some important early work on systems analysis, including mission and design studies, was conducted at NOSC under the sponsorship of ONR, NAVAIR, and NAVSHIPS.[10] The greatest amount of research and model tests has been conducted at DTNSRDC, and the largest number of design studies have been conducted at NAVSEC. NOSC has also contributed heavily throughout the SWATH program. These research and design studies will be discussed in more detail later.

SWATH Concept

The basic SWATH concept is illustrated in figure 10. Characteristic of all SWATH designs are two hulls which provide the primary displacement. Since the hulls are submerged, wavemaking drag is reduced. An aft-mounted stabilizing fin, or fins, provides dynamic stability. Small canard fins, which aid in improving dynamic damping of motion and controlling trim, are optional. One, two, or more surface-piercing streamlined struts per side provide static stability in heave, pitch, and roll, and support a cross structure sufficiently high above water to minimize wave impact and deck wetness. Many variations are possible in the size and shape of the individual components, thus allowing the design to be optimized for different mission performance requirements.

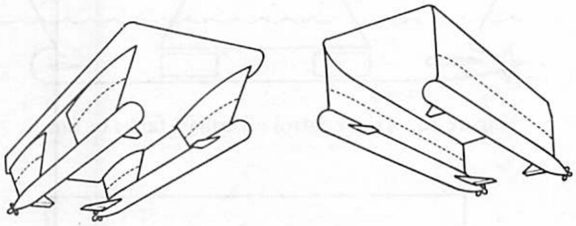

Figure 10. SWATH concept.

The deck area of SWATH ships tends to be large relative to that of equal-displacement monohulls, figure 11. The monohulls require a narrow beam in order to minimize wave drag at higher speeds. Also, the beam and draft of a SWATH ship tend to be greater than those of a monohull, figure 12. Consequently, access to shallow harbors, docking in limited spaces, and drydocking of larger versions could be problems.

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*The SSP was designed by NOSC personnel at San Diego and Hawaii, with the aid of personnel from the Pearl Harbor Naval Shipyard. Design review and verification assistance were received from NAVSEC and DTNSRDC.

**Called the Naval Undersea Center at that time.

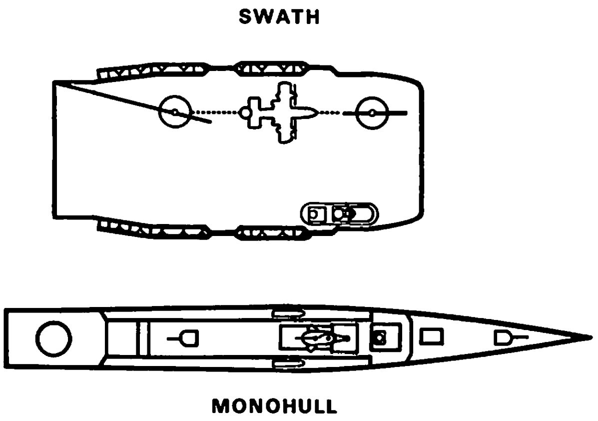

Figure 11. Comparison of deck areas.

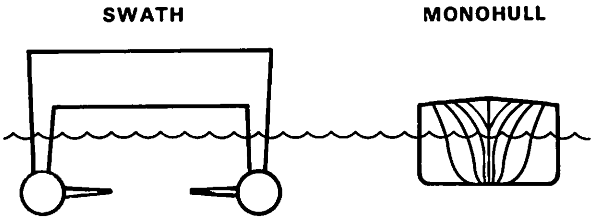

Figure 12. Comparison of beam and draft.

Trim and pitch changes are small, unless large load changes are made, in which case either water ballast, or control fin movement when underway, will maintain the SWATH at its normal attitude, figure 13. SWATH craft have sufficient waterplane areas to permit loading or off-loading helicopters, men, and equipment weighing up to around 4–8% of the full-load displacement without reballasting. Also, SWATH is sensitive to unanticipated weight growth, the impact of which can be minimized by adding hull extensions (figure 14), such as those which were placed on the SSP.

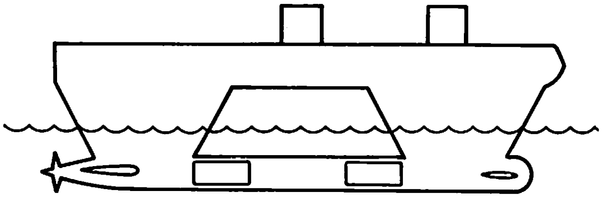

Figure 13. Trim control via ballast tanks or fins.

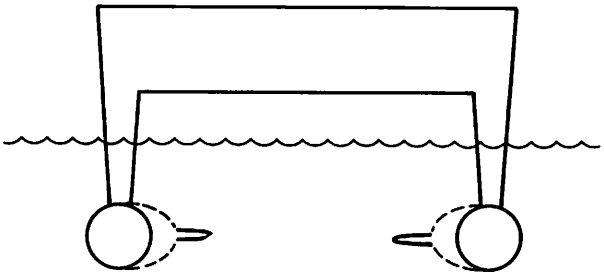

Figure 14. Sideward hull extensions.

Model Tests

The David Taylor Naval Ship Research and Development Center (DTNSRDC) and the Naval Ocean Systems Center have conducted extensive model tests. Over a dozen different SWATH models have been built and tested. SWATH components, such as struts and submerged hulls, were tested both individually and in various combinations. Some models were towed, others were self-propelled or radio controlled. Many measurements were made, including drag and other forces, hydrodynamic moments, structural loads and stresses, motion in waves, impact pressures, control characteristics, power requirements, wind effects, towing, and anchoring. Corresponding theory and computer programs have been developed in most cases.

Model tests show that in calm water SWATH ships require more power than equal displacement monohulls at low-to-moderate speeds, and equal or less power than monohulls at moderate-to-high design speeds. Also, results show that monohull drag increases significantly with increasing sea state, while SWATH drag increases very little.

The earliest Navy-sponsored SWATH model tests were conducted in 1969 (reference 10, Part II). These tests were conducted on various versions of towed tandem-strut models, and demonstrated that the designs tested were indeed stable at all test speeds, that stabilizing fins were needed, that motion was larger in following waves than in head waves, that an increased fore-and-aft spacing between struts reduced the following sea motions, that the larger stabilizing fins tested produced the smallest trim changes, that the forces required for a level ride in waves were low enough to be controllable by fins, and that a reasonable value for the roll metacentric height was around 0.75 hull diameter.

Another early model was the 5-foot radio-controlled model of the SSP, which was first tested in 1970 and provided the basic model information needed for designing the SSP. Results showed that its behavior in all modes of operation in all waves tested was acceptable; and that the model was highly maneuverable, banked naturally into turns, could rotate at rest about its vertical axis, could reverse without problems, would be safe under extreme wave and wind conditions, satisfied damaged stability criteria under simulated conditions, could be anchored, and was controllable in heave, pitch, and roll.[8,9,11,12]

Tests on an 11-foot self-propelled model of the SSP were later conducted in the spring of 1971* at DTNSRDC to validate the SSP design and provide additional coefficient data for the design of an automatic control system. The motion results showed good behavior in the design sea state of 4.

A large number of model tests were conducted at DTNSRDC on various single-strut and one tandem-strut SWATH designs. These included tests on drag, motions, impacts, turning, propulsion, hydrodynamic coefficients, and loads.[13-16] The results, in general, verify the characteristic reduced-motion behavior attributed to SWATH ships, and add significantly to the literature on SWATH. SWATH VII, in tests conducted at Hydronautics, is shown by Kirkman et al[17] to have a relatively low drag coefficient over a wide speed range and a propulsive coefficient high relative to that of monohulls.

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*Documented by a series of unofficial DTNSRDC T&E reports.

SWATH Performance Predictions

Drag and Power

Theoretical predictions based on potential flow have correlated well with experimental data, probably because of the relatively thin struts, fins, and hulls that can be closely represented by distributions of sources and sinks. Several computerized drag programs exist, among them those of Chapman,[18] Lin and Day,[19] and Pien and Lee,[20] arranged in the order of increasing complexity. The simplified Chapman theory has been shown to provide good correlation with data on single and tandem struts, single and parallel hulls, various hull and strut combinations, and complete SWATH models. At higher speeds, allowance must also be made for spray drag, which has been explored by Chapman.[21]

The propulsive coefficient for SWATH ships is reported by Hawkins and Sarchin[22] to be 0.75, while the corresponding value for monohulls is reported to be only 0.62 to 0.67. This is apparently due to the improved inflow conditions to the SWATH propellers and the fact that they can be designed to recover the hull boundary layer energy.

A very approximate, nondimensional representation of SWATH vehicle efficiency versus displacement Froude number is reproduced in figure 15 from reference 1, showing how SWATH compares with other types of craft with respect to vehicle efficiency (i.e., displacement X speed ÷ power). The result shows, in general, that SWATH ships require more power than monohulls up to a displacement Froude number of 1.2, and less power above that value.

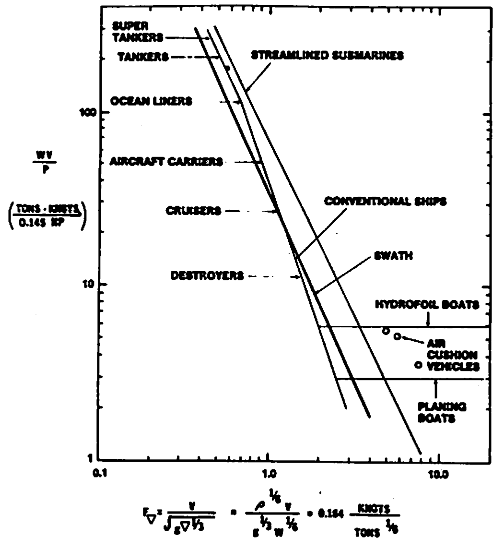

Figure 15. Vehicle efficiency vs Froude number.

Since monohull drag increases markedly in rough water, while SWATH drag does not, the crossover point for the more realistic case of rough water would occur at a somewhat lower displacement Froude number. For more exact comparisons for calm-water powering, specific SWATH and monohull designs should be selected and analyzed.

It is possible to reduce SWATH drag at low-to-moderate speeds by hull/strut shaping, wherein the wave drag of the struts can be partially cancelled by wave drag interference from the hulls; however, this type of hull/strut shaping often increases the drag at higher speeds. Results indicate that shaping is about equally effective for either the two- or four-strut SWATHs, but that the four-strut case seems to require significantly larger hull diameter variations, Parnell.[23] In the high-speed range, the tandem-strut designs appear to have equal or less drag than equivalent one-strut designs, although more studies are needed to verify this.

Loads and Structures

Results to date indicate that the principal hydrodynamic loads are slamming on the cross structure and the side loads on the struts. The hydrostatic load on the hulls and struts due to water depth is also a significant factor. Other principal loads are local deck loads. For air cushion craft, Mantle[24] shows that design impact pressures are about 1 psi per knot. For SWATH, Aronne, Lev, and Nappi[25] recommend using a 100 psi design pressure on forward plate panels and 1,000 to 1,500 psf for the bottom and forward supporting structure. They calculated a "basic" structural weight fraction for the 4,000 ton ship "B" to be 38%, 31%, and 23%, respectively, for steel, hybrid steel/aluminum, and aluminum. The total structural weight fraction, including secondary structure, would be around 1.2 to 1.4 times these values. The hybrid design is similar to that of the SSP where the cross structure is aluminum and the struts and lower hulls are steel. The all-steel version would be made of high tensile strength steel (HTS). Serrell[26] has independently estimated the total structural weight fraction for an all-aluminum 3,000 ton SWATH to be 0.33, which is in reasonably good agreement. Studies indicate that a trade-off between weight and cost might lead to the hybrid steel and aluminum structure in many cases.

Higdon[27] presents experimental data which show that the total side force on one side of a typical tandem-strut SWATH in beam waves at rest is 0.16Δ in 40:1 length-to-height-ratio waves, and about twice that for 20:1 waves, where Δ is the total model displacement. Linearly extrapolating to the worst case of 13:1 waves, which are breaking waves, the side load would be around 0.49 Δ. This is probably a reasonable design value for various tandem-strut SWATHs; however, the actual load for a specific design should be calculated using theory such as that developed by Higdon.[28] For the case of a single-strut SWATH, the side load is more accurately calculated using the theory by Lee and Curphy[29] who present a graph indicating that the maximum side load on a SWATH II model (extrapolating linearly to 13:1 waves) would be about 1.0 Δ. SWATH structural weight tends not to be a strong function of side load, but it is necessary to accurately estimate the side load for structural design purposes. The difference between the Higdon and the Lee and Curphy theories is that the latter include wave diffraction from a strut while the former assumes that the approaching waves are unaffected by the strut presence. Consequently, it would appear that wave diffraction, with the associated side load, increases as the gap between the tandem struts reduces toward zero, thereby approaching the case of a single-strut SWATH.

Hydrodynamic Coefficients and Motion

Several reports on SWATH motion have been written, including that by Salveson,[30] who compares the motion of SWATHs and monohulls. A recent report by Lee and Curphy[29] presents a comprehensive treatment of theory for predicting the hydrodynamic coefficients and motions of SWATH ships. The theory is shown to agree well with experiments, except for the following sea motion case, for which the authors recommend improvement in the theory. It is shown that SWATH motions generally tend to be significantly less than monohull motions, and that SWATH motions are largest in the following waves, where they may approach the monohull values. The authors verify the results of earlier reports[10,11,31] that fins are necessary for stability at high speeds, and that fins significantly reduce resonance motions at forward speeds.

Lift and trim forces on SWATH ships are shown by Chapman[32] to change significantly with speed, and thus should be included in the design process. There is a net sinkage force caused by the surface-piercing struts which dominates the dynamic lifting force on the submerged hulls. This effect was observed in the early SWATH experiments.[10,11] Results on the 5-foot radio-controlled SSP model showed that deflections of the front canards and aft flaps will counteract these sinkage and trim forces.

Olson[33] analyzed the effects of ship motion on human effectiveness, showing that the motion of monohulls in large waves can significantly affect personnel. He cites the need for more research in this area. Fatigue begins when the average roll exceeds 6° and becomes very significant beyond 10°. Motion sickness is most predominant at motion periods of around 5–6 seconds. Results of work by Human Factors Research, Inc., were cited to show that 25% of the subjects tested became sick when the vertical RMS acceleration exceeded 0.1g, and 50% at an RMS acceleration of about 0.2g. Olson[34] has recently extended his analysis to show that SWATH ships should markedly alleviate this problem and solve motion problems related to equipment as well.

The effect of ship motion on reducing monohull speed in head waves is shown in figure 16. Speed reduction data from 15 ships were obtained from reference 35 and replotted in dimensionless form as a function of the average wave height in feet divided by the one-third power of the ship displacement in tons; thus, a 1,000-ton ship operating in 10-foot waves would correspond to a value of 1 on the abscissa. Estimates of the speed change of a SWATH in waves with automatic control are superimposed on the graph. In a following sea, a SWATH would appear equally good unless it did not have automatic control, in which case its speed would have to be reduced from the SWATH curve shown in figure 16.

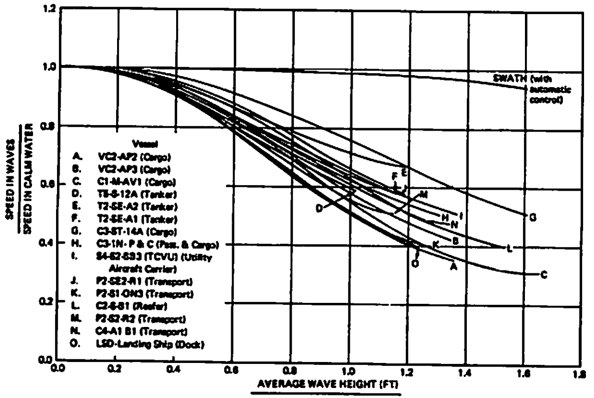

Figure 16. Operational data of ship speed reduction in head seas.

Maneuvering and Automatic Control

Radio-controlled SSP model tests indicate a turning diameter of 4.5 ship lengths at a 23-knot scaled speed entering the turn.[8] Full-scale SSP data indicate turn diameters of 6 and 9 lengths at an initial speed of 19 knots when banked into the turn, and not banked, respectively.* The latter is close to the 10-length turn diameter reported by Fein and Waters[36] for the single-strut SWATH VI A model at design speed with spade rudders and zero bank; smaller turn diameters are predicted at lower speeds. Since a SWATH is shorter than equal-displacement monohulls (with turn diameters of 5 to 6 lengths), these turn diameters are considered acceptable.

At zero speed, a SWATH can rotate about its vertical axis using differential propeller thrust. As speed increases, the rudders become more effective relative to the propellers. When a speed of several knots is reached, the rudders provide the majority of the control. This is advantageous since if one propeller is shut down, a SWATH can continue on a straight course using rudder control if the speed is above a few knots. Also, because of excellent thrust control at low speed, SWATHs may not need bow thrusters for certain kinds of missions that require station keeping or precise maneuvering near docks.

Chapman[37] has shown that the sideforce coefficient of struts can vary by as much as a factor of three, depending on Froude number, and has developed theory for predicting this result. Consequently, the theoretical prediction of turning diameter is not as simple as one might expect.

Higdon[10,11,31] has pioneered the application of automatic control to SWATH, and shown that nearly full control is possible over heave, pitch, and roll. Significant reductions in motion and acceleration are possible beyond the already-reduced motions of SWATHs over monohulls. The relatively large motions of SWATHs when operating at high speed in large following waves can be reduced by as much as a factor of 10 by using automatic control. Also, slamming and propeller ventilation in large waves can be delayed another sea state or more by using automatic control. These results, together with fin sizing criteria by Higdon,[38] have been verified by the more recent work by Lee and Martin[39] and by Lee and McCreight.[40]

SSP Prototype Results

In general, the SSP results have verified model tests and theory. Other papers to be presented by Fein, McCreight, and Kallio,[41] Higdon,[42] and Hightower and Seiple[43] will cover the SSP motions without automatic control, motions with automatic control, and operational experiences, respectively.

The experience of riding on the SSP and handling its controls is unique. In large waves, it negotiates crests and troughs with only a fraction of the motion one would normally expect. Equipment and supplies are lying around loose that would normally be tied down on a monohull. The response to the rudders is positive and immediate, without the sideslip and overshoot typical of monohulls; the craft banks naturally inward on turns rather than outward as displacement monohulls do. Perhaps the most remarkable experience is to oscillate the canards between their full-up and full-down deflections and watch the height of the cross structure above water vary smoothly from 0 to around 15 feet and back again. Differential deflections of either the canards or flaps will make the SSP smoothly roll to its limit either way, where the cross structure begins to hit the water on one side and the lower hull begins to emerge on the other. This high degree of control is indicative of the motions that can be overcome with the control system in order to provide a near-level ride. After an hour or so of experience, it is possible to manually control the SSP to near-level flight. However, it is much easier to let the automatic control system take over, including the rudder control, so the operation can be "hands off." Below, the view through the acrylic dome is remarkable, especially in large waves. One can see the waves traveling up and down on the opposite strut. If

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*Personal communication on 2/17/78 from J. Fein, DTNSRDC.

luck is good, one may see wild porpoises coasting just ahead of the dome, getting a free ride from the pressure field.

Figure 17, reproduced from reference 9, shows the reasonably good correlation between SSP drag and earlier tests on the 5-foot SSP model. The data were reduced from SSP power measurements utilizing the propulsive coefficient obtained from tests on the 11-foot model at DTNSRDC.

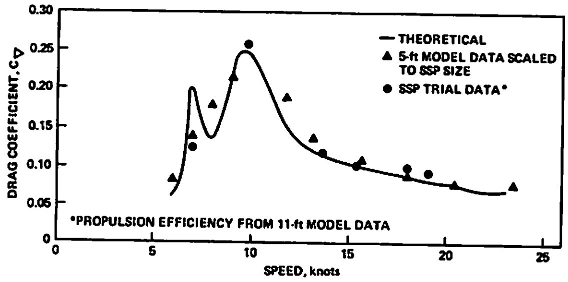

Figure 17. SSP "displacement" drag coefficient vs speed.

Stensen[44] reports that the powering data were also in good agreement with the 11-foot model drag tests. The SSP reached a speed of 19.08 knots with 2936 HP at 0.75 of the design shaft torque. (The shaft torque was limited by a special propeller shaft section that was used for shaft torque measurement.) Stensen also reports that the extrapolated speed at the full design power of 4200 HP would have been about 23 knots. Also measured were tactical turning diameters of 10–12 lengths (30° rudder) at initial speeds of 8 to 14 knots, which are significantly larger than the 6–9 length turn diameters (35° rudder) presented earlier for an initial speed of 16 knots. This difference is probably due to the rudder angle differences and the possibility that the turn rate is reduced when the speed is in the vicinity of the "drag-hump" speed of 10 knots (see figure 17).

Fein and Waters[45] report that the damping of the SSP was so large that determination of the natural periods was difficult. Based on less than a full cycle, the estimated natural period in pitch varied from 8.8 seconds at 9.75 knots to 13.6 seconds at 18 knots. The roll natural period varied from 12 seconds at 9.75 knots to 19 seconds at 18 knots. When underway, the pitch and heave motions become a single highly damped motion. The control surfaces performed about as expected, so adequate control was predicted for automatic control which would be installed at a later date.

Kallio[46] reported on the seakeeping trials of the SSP which were conducted at speeds from 9.5 to 16.5 knots in its design sea state of 4 with a significant wave height (average 1/3 highest) of about 6 feet. The motions in head and bow quartering seas were less than in stern quartering and following seas, as expected. Also, very few samples of wave impact data were obtained, again as expected. The maximum recorded significant heave (average 1/3 highest) was ±3 feet in beam seas, pitch was ±5° in a following sea, roll was ±5° in a beam sea, heave acceleration was ±0.09g, bow vertical acceleration was ±0.11g, sway acceleration was ±0.05g, surge acceleration was ±0.04g, and the maximum recorded impact pressure was 9.8 psi for about 1 second. The propellers ventilated twice in stern quartering seas, but the problem was corrected by changing the trim. All tests were conducted without automatic control and with the canards and flaps fixed at their trim angles for each speed.

Design Tradeoffs

Discussion

An important aspect of the design process is to determine the effect of changing various design parameters. For example, how does a change in speed trade off against displacement? Alternatively, how does range affect payload, or how does structural weight affect range? The following is a simplified analytical approach which provides approximate answers to these kinds of questions. This approach is based upon the generalized design procedure by Lang,[47] and can be extended to cover the more complex design cases.

Basic Equations

Let the displaced weight W of a ship be defined as

$$W = W_a + W_s + W_p + W_f \qquad (1)$$

where,

W_a = weight of all items which are essentially independent of the displacement, speed, or range. W_a includes such items as payload, men, outfitting, supplies, and auxiliaries.

W_s = weight of all structural-like items that vary essentially with displacement, including primary and secondary structure, anchors, and rudders.

W_p = weight of propulsion items that vary with power, including engines, shafts, and propellers.

W_f = weight of the fuel.

$$\text{Let } W_p = \alpha P = \frac{\alpha C_d}{\eta}\left(\frac{W}{\rho g}\right)^{2/3}\frac{\rho}{2}V^3 \qquad (2)$$

$$\text{and } W_f = \beta\frac{PR}{V} = \frac{\beta C_d}{\eta}\left(\frac{W}{\rho g}\right)^{2/3}\frac{\rho}{2}V^2 R \qquad (3)$$

where α is the weight per unit of installed power P, C_d is the drag coefficient based on volume, ρ is the mass density of seawater, g is the acceleration of gravity, V is ship speed, β is the fuel weight per unit power and time, R is the range, and η is the propulsive efficiency times the transmission efficiency.

Substituting equations (2) and (3) into (1), dividing by W, and defining $W_s/W = W_s'$,

$$1 = \frac{W_a}{W} + W_s' + \frac{C_d\rho^{1/3}V^3\alpha}{2\eta g^{2/3}W^{1/3}} + \frac{C_d\rho^{1/3}V^2\beta R}{2\eta g^{2/3}W^{1/3}} \qquad (4)$$

modifying equation (4),

$$\frac{W_a}{W} + \left(\frac{W_a}{W}\right)^{1/3}\gamma = 1 - W_s' \qquad (5)$$

where

$$\gamma = \frac{C_d \rho^{1/3} V^2}{2\eta g^{2/3} W_a^{1/3}} [V\alpha + \beta R] \qquad (6)$$

This equation is plotted in figure 18. The results show, for example, that if $W/W_a = 6$ and $W_s' = 0.4$, then $\gamma = 0.8$. Now, if γ were increased by 25%, due to changes in C_d, η, V, R, α, or β, then the displacement would increase 50%. Alternatively, if γ reduced by 25%, the displacement would reduce by 33%. Similarly, reducing W_s' to 0.2 would reduce displacement by 45%.

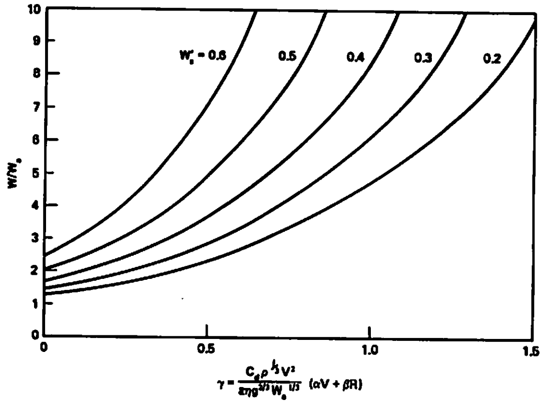

Figure 18. Displacement to W_a ratio for ships.

Figure 18 can also be used to compare monohull and SWATH ships. For example, assume that a monohull and a SWATH are designed for the same values of W_a, V, R, α, and β. Let the monohull have $W_s' = 0.3$ and $\gamma = 1.0$. Assume the equivalent SWATH has $W_s' = 0.4$, $C_d = 5\%$ less, and $\eta = 10\%$ greater than the monohull. Figure 18 shows that the SWATH will displace 3% less than the monohull. Alternatively, if the C_d for SWATH had been 5% greater rather than 5% smaller than for a monohull, the SWATH displacement would have been 15% greater than the monohull.

A method for more directly determining the effect of a change in one parameter on another is to modify equation (4) by multiplying and dividing each variable term by the same term having the subscript 0 to designate a baseline design, and then adding the subscript 1 to the original term to designate a new design. Thus, equation (4) becomes

$$1 = \frac{\frac{W_{a1}}{W_{a0}} \cdot \frac{W_{a0}}{W_0}}{\frac{W_1}{W_0}} + \frac{W'_{s1}}{W'_{s0}} W'_0 + \frac{\frac{C_{d1}}{C_{d0}}\left(\frac{V_1}{V_0}\right)^2}{\frac{\eta_1}{\eta_0}\left(\frac{W_1}{W_0}\right)^{1/3}} \left(\frac{\rho^{1/3} C_{d0} V_0^2}{2g^{2/3} \eta_0 W_0^{1/3}}\right)$$

$$\left(\frac{\alpha_1}{\alpha_0}\frac{V_1}{V_0} V_0 \alpha_0 + \frac{\beta_1}{\beta_0}\frac{R_1}{R_0} \beta_0 R_0\right) \qquad (7)$$

Substituting the baseline design values for equations (2) and (3) into (7), and letting primes denote weight fractions,

$$1 = \frac{W_0}{W_1}\frac{W_{a1}}{W_{a0}} W'_{a0} + \frac{W'_{s1}}{W'_{s0}} W'_{s0} + \frac{\eta_0}{\eta_1}\frac{C_{d1}}{C_{d0}}\left(\frac{W_0}{W_1}\right)^{1/3} \left(\frac{V_1}{V_0}\right)^2$$

$$\left[\frac{\alpha_1}{\alpha_0}\frac{V_1}{V_0} W'_{po} + \frac{\beta_1}{\beta_0}\frac{R_1}{R_0} W'_{f0}\right] \qquad (8)$$

Equation (8) can be used to show how a change in any one variable can affect any other variable. For example, the change in displacement resulting from a change in any one variable, while keeping all the remaining terms fixed, is shown in figure 19 for the case of $W_s{}'_o = 0.40$, $W'_p{}_o = 0.10$, and $W_f{}'_o = 0.15$ where $W_a{}'_o = 1 - W_s{}'_o - W_p{}'_o - W_f{}'_o = 0.35$. The result shows that an individual increase of 20% in each of W_a, W_s', η, C_d, V, R, X, α, and β will change the displacement by 15, 25, -8, 12, 42, 10, 6, and 10%, respectively. Alternatively, reducing W_s' from 0.40 to 0.30, such as by using more aluminum, would reduce displacement by 20%.

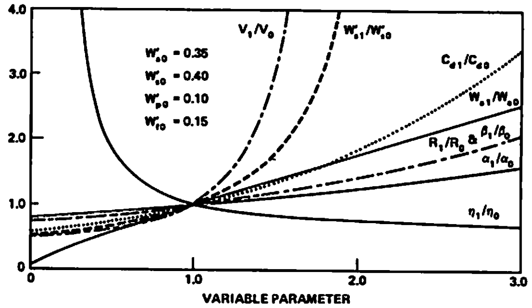

Figure 19. Displacement change as a function of design parameter changes ($W_s{}'_o = 0.40$).

Figures 20 and 21 also originated from equation (8), and show the effects of the variables on range and payload, respectively, for the same baseline design as in figure 19. The results show that both range and payload are greatly affected by speed and displacement. The figures can also be used to determine the effects of simultaneous changes in the parameters, such as an increase in range and a reduction in structural weight.

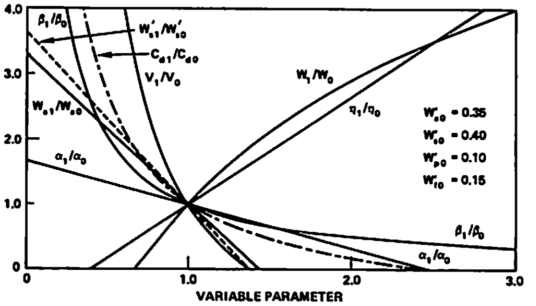

Figure 20. Range change as a function of design parameter changes ($W_s{}'_o = 0.40$).

Figure 22 shows that speed is not affected by changes in the design parameters as much as W, W_a, and R were. However, changes in W, η, W'_s, and W_a have the greatest effect on speed.

Changing the baseline design from $W_s{}'_o = 0.40$ to 0.30. as in figure 23, appears to produce little change from figure 19, except for the curve of $W_s{}'_1/W_s{}'_o$ which has become less critical.

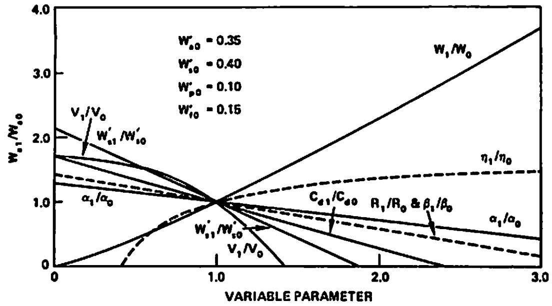

Figure 21. Payload change as a function of design parameter changes ($W_s{}'_o = 0.40$)

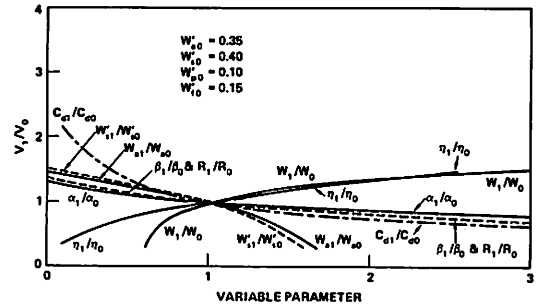

Figure 22. Velocity change as a function of design parameter change ($W_s' \doteq 0.40$).

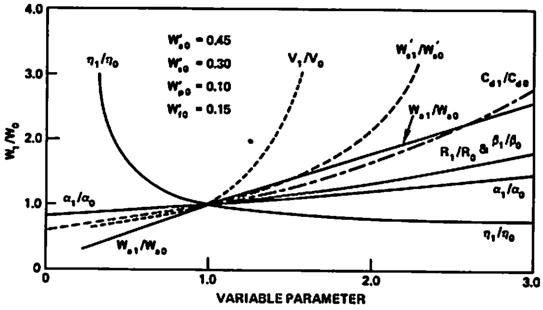

Figure 23. Displacement change as a function of design parameter changes ($W_s{}'_o \doteq 0.30$).

The new values of W_p' and W_f' resulting from a design change can be calculated from the following equations which were derived from equations (2) and (3):

$$\frac{W'_{p1}}{W'_{p0}} = \left(\frac{C_{d1}}{C_{d0}}\right)\left(\frac{V_1}{V_0}\right)^3\left(\frac{\alpha_1}{\alpha_0}\right)\left(\frac{\eta_0}{\eta_1}\right)\left(\frac{W_0}{W_1}\right)^{1/3} \tag{9}$$

$$\frac{W'_{f1}}{W'_{f0}} = \left(\frac{C_{d1}}{C_{d0}}\right)\left(\frac{V_1}{V_0}\right)^2\left(\frac{\beta_1}{\beta_0}\right)\left(\frac{\eta_0}{\eta_1}\right)\left(\frac{W}{W_1}\right)^{1/3}\left(\frac{R_1}{R_0}\right) \tag{10}$$

Modified Equations

For propulsion systems in which one power source is used for cruising and another for maximum speed, two power and two fuel terms are needed in the weight equation. Using the subscripts c and m to correspond to the cruise and maximum speed conditions, respectively, equations (2) and (3) become

$$W'_p \doteq \frac{C_{dc}}{2\eta_c}\cdot\frac{V_c^2\rho^{1/3}}{g^{2/3}W^{1/3}}\cdot\alpha_c V_c + \frac{C_{dm}}{2\eta_m}\cdot\frac{V_m^2\rho^{1/3}}{g^{2/3}W^{1/3}}\cdot\alpha_m V_m \tag{11}$$

$$W'_f \doteq \frac{C_{dc}}{2\eta_c}\cdot\frac{V_c^2\rho^{1/3}}{g^{2/3}W^{1/3}}\beta_c R_c + \frac{C_{dm}}{2\eta_m}\cdot\frac{V_m^2\rho^{1/3}}{g^{2/3}W^{1/3}}\beta_m R_m \tag{12}$$

Modifying these equations,

$$W'_p = \frac{C_{dm}}{2\eta_m}\cdot\frac{V_m^2\rho^{1/3}}{g^{2/3}W^{1/3}}\cdot\alpha_m V_m \left[1 + \frac{C_{dc}}{C_{dm}}\cdot\frac{\eta_m}{\eta_c}\left(\frac{V_c}{V_m}\right)^3\cdot\frac{\alpha_c}{\alpha_m}\right] \tag{13}$$

$$W'_f = \frac{C_{dm}}{2\eta_m}\cdot\frac{V_m^2\rho^{1/3}}{g^{2/3}W^{1/3}}\cdot\beta_m R_m \left[1 + \frac{C_{dc}}{C_{dm}}\cdot\frac{\eta_m}{\eta_c}\left(\frac{V_c}{V_m}\right)^2\frac{\beta_c}{\beta_m}\frac{R_c}{R_m}\right] \tag{14}$$

Equations (13) and (14) can be substituted into their corresponding terms in equations (4) through (8) and then used for answering a more complex set of design questions relating to tradeoffs with the cruise and maximum speed propulsion systems. However, for some such questions, the original equations (4) through (8) can still be used. For example, if the cruise system and ship displacement were to be fixed in a design tradeoff, the maximum speed system could be treated as the sole propulsion system, wherein the cruising power plant and its associated fuel would be combined into the W_a term.

Future Applications and Potential

Combatant Versions

SWATH ships for future naval operations could range in displacement from 500 tons to perhaps 20,000 tons or more. Analysis by Warnshuis suggests that all sizes of SWATH ships are potentially useful, and that displacements around 2,000 to 4,000 tons would be of special interest.[48] Figure 24* shows an artist's version of a 2,500-ton platform for ASW escort missions.[22] It would carry three helicopters, defensive air and surface weapons, a variety of underwater sensors, and antisubmarine weapons. A modified version (figure 25)* could satisfy Coast Guard cutter requirements for enforcement of the new 200-mile offshore limit laws. Figure 26 illustrates a future 3,500-ton platform described by Sturgeon[49] that would allow future V/STOL support aircraft to be refueled and rearmed near points of need. The deck run, plus a substantial wind-over-the-deck, would allow V/STOL aircraft to carry large payloads.

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*Courtesy of DTNSRDC

Figure 24. 2,500-ton SWATH frigate.

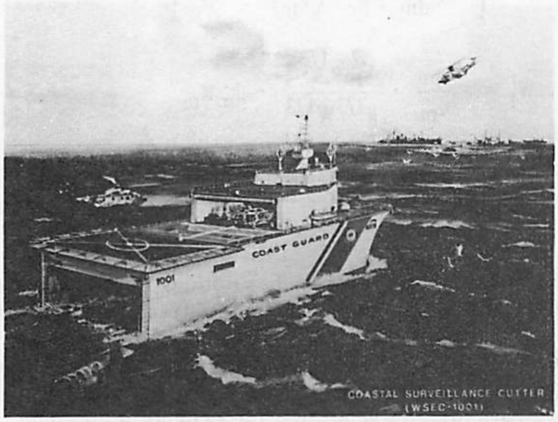

Figure 25. 2,500-ton SWATH coastal surveillance cutter.

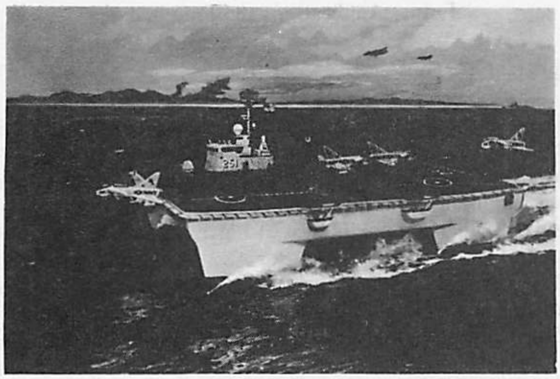

Figure 26. 3,500-ton SWATH V/STOL carrier.

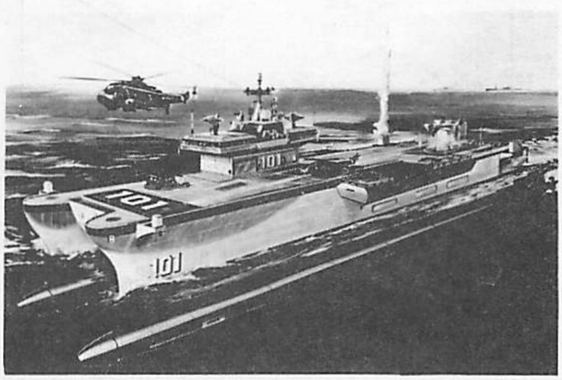

Figure 27. 12,000-ton SWATH V/STOL carrier.

The 12,000-ton artist's version shown in figure 27* could provide permanent basing for 10–20 V/STOL aircraft and helicopters. Modular outfitting of support systems would permit different types of aircraft to be changed quickly to meet mission requirements. A smaller, 7200-ton "ski jump" carrier is shown in figure 28* which would be designed to support type A V/STOL aircraft and helicopters. It would have a flight deck length of 325 feet and a beam of 106 feet.

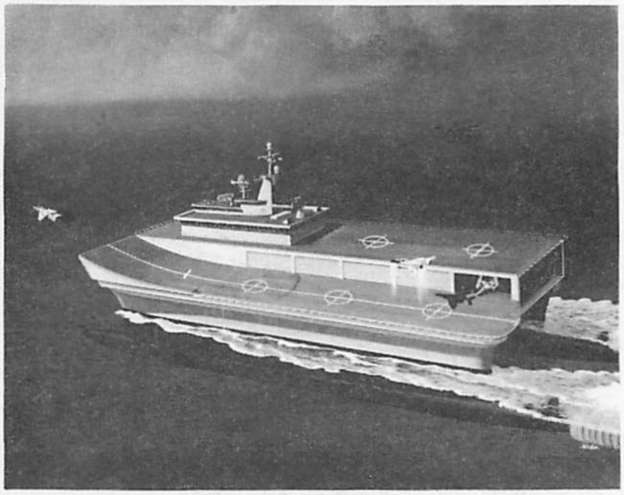

Figure 28. SWATH V/STOL carrier (ski-jump deck).

The 500-ton SWATH shown in figure 29 is another potential application which could be armed with vertically launched surface-to-air missiles and the latest cruise missile system. It would be a potent adversary in open-ocean or inshore surface warfare. The 1,000-ton SWATH shown in figure 30 demonstrates another unusual capability of SWATH ships, namely that of towing very large pods, as conceived by Warnshuis,[50] which might contain ordnance, surveillance equipment, or fuel.

Since basically the only new feature is the shape, current technology can be used to construct these SWATH ships. The large above-water cross structure is readily accessible and lends itself to modular outfitting. Using the modular approach for outfitting, the basic design of figure 26 has been investigated for a variety of naval applications.[49]

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*Courtesy of DTNSRDC

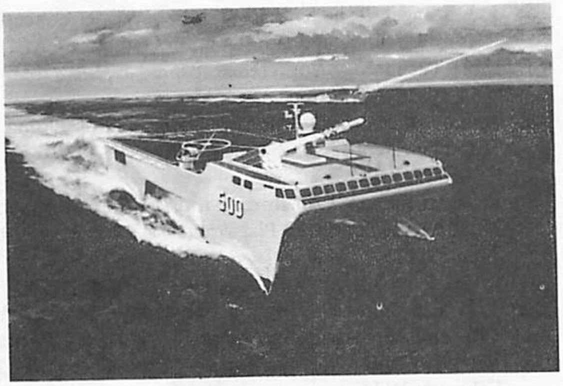

Figure 29. 500-ton SWATH.

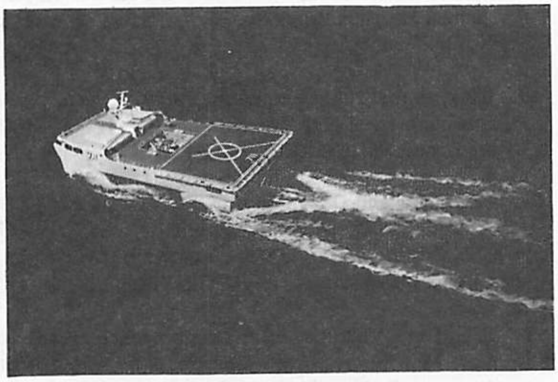

Figure 30. 1,000-ton SWATH with towed pod.

Mission-independent subsystems, including accommodations, are arranged around the perimeter of the cross structure on each of the two decks, while the modular mission subsystems are centralized in the payload bays located in the central region of each deck (figure 31). Thus, a single mass-produced structure could be outfitted to be used for V/STOL aircraft operations, ASW, surveillance, medical support, troop basing, mine countermeasures, logistic support, and other applications.

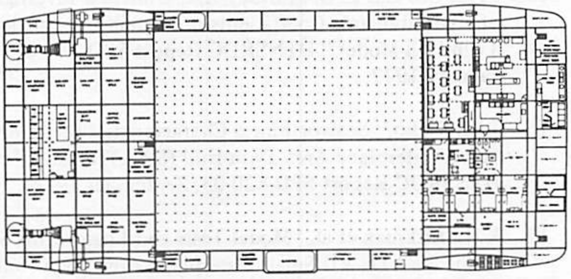

Figure 31. 3,500-ton SWATH modular outfitting arrangement.

The V/STOL and helicopter airbase potential of SWATH ships, showing a variety of new outfitting concepts and designs, is discussed by Warnshuis and Sturgeon.[51] A more recent paper on SWATH for V/STOL aircraft was published by Childers, Gloeckler, and Stevens,[52] who further describe and discuss the advantages of SWATH for this application. Lamb[53] presents a summary of SWATH technology, which augments earlier summaries by Stevens,[54] Leopold et al,[55] Sarchin et al,[56] and others[10,22] showing how SWATH can improve the general operability of surface ships. Some of the latest design work on SWATH at the Naval Ship Engineering Center (NAVSEC) is presented by Anderson, Kerr, and Kennell,[57] which describes the various design aspects and tradeoffs.

In general, the differences in performance characteristics between the single and tandem SWATH designs, when designed for a particular application, are small compared to the differences between either type and a monohull. The selection of one or the other SWATH configuration will depend upon the emphasis given to each aspect of performance for a specific mission application. Trade-off studies conducted during the early phases of design will identify which configuration is best suited for the intended use.

A fundamental difference between the two generic SWATH forms is that tandem-strut designs tend to have less waterplane area for a given displacement, which leads to a more dispersed configuration. This, in turn, leads to the following areas where differences have been identified: (a) single-strut SWATHs have a higher ton-per-inch of immersion, which provides greater overload capacity and less sensitivity in draft to load changes; (b) tandem-strut SWATHs have longer natural periods in roll and heave, which, together with the gap between the tandem struts, can lead to smaller roll and heave motions; and (c) tandem-strut SWATHs have smaller turning diameters. Also, the low-to-moderate-speed powering requirements tend to be somewhat lower for the single-strut designs. At higher speeds, powering requirements are approximately the same or perhaps somewhat lower for tandem-strut designs.

According to the SWATH Program Manager,* it is felt that it is time to build a multi-thousand-ton SWATH development platform for full-scale evaluation of prediction techniques and operational effectiveness. Evaluation would cover the design, construction, and cost; and operations with aircraft, weapons, and sensor systems.

Noncombatant Versions

A natural application of SWATH ships is for oceanic research because of its low-motion characteristics, large deck areas and internal spaces, adaptability for a center well, and helicopter support capability. Figures 32 and 33 show possible 500-ton and 3,000-ton versions.[58]

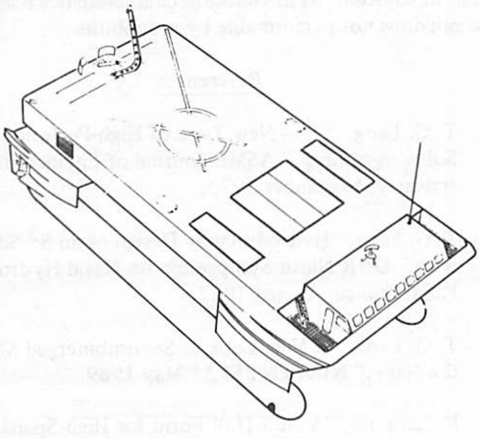

Figure 32. 500-ton SWATH oceanographic research ship.

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*A. T. Strickland, NAVSEASYSCOM 03221, Acting for L. Benen.

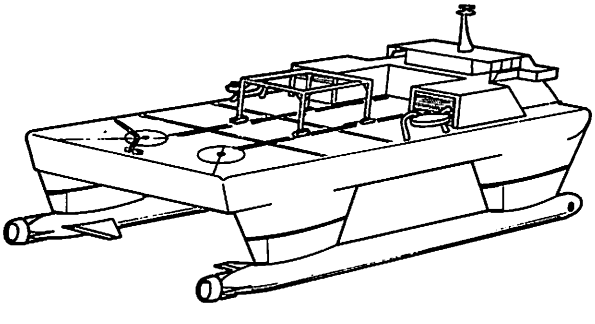

Figure 33. 3,000-ton oceanographic research ship.

Another possible application is for range support, such as the SSP. Baitis et al[59] conducted a comparison study of six ship designs to satisfy a work boat requirement for a Navy range in Hawaii. A 20-knot, 1286-ton SWATH design was selected as being the best candidate.

Various other Navy uses include offloading for a container ship, acoustic measurements, oceanic surveys, and supply. In general, SWATH would be applicable for most uses requiring low motion in waves, large deck areas, and large internal volumes.

Summary*

SWATH technology has advanced considerably in the last several years, and has been highlighted by the development of the SSP KAIMALINO, which has satisfied all expectations and demonstrated low motion in large waves with the ability to carry out a wide variety of range support tasks. Some new approaches toward making design tradeoffs are presented which show the design ramifications of changing such items as speed, range, payload, type of propulsion system, drag, and propulsive efficiency.

The SWATH ship concept provides a means for designing small, low-cost ships that can be modified quickly to meet a wide variety of mission requirements in either the combatant or noncombatant areas, and is useful over a wide range of sizes. In addition, its low-motion characteristics may permit new missions not performable by monohulls.

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** NUC and NOSC TNs are informal documents intended chiefly for internal use.

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