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HYDRODYNAMICS OF THE 190-TON STABLE SEMISUBMERGED PLATFORM (SSP)

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HYDRODYNAMICS OF THE 190-TON STABLE SEMISUBMERGED PLATFORM (SSP)*

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Abstract

The form, hydrodynamic design, and predicted performance of the 190-ton Stable Semisubmerged Platform (SSP) are described and analyzed. Design criteria are presented for the twin submerged hulls, four surface-piercing struts, bow section of the above-water cross structure, aft stabilizing fin and flaps, forward-mounted canard control surfaces, rudders, and the controllable and reversible propellers. Hydrodynamic loads and motion in waves are analyzed. The overall design is evaluated in light of design experience, model test results, and preliminary operating experience with the 190-ton SSP. The 190-ton SSP is shown to have significantly reduced motion in waves, increased rough-water speed, and more deck space and internal volume than conventional monohulls.

I. Introduction

The 190-ton SSP, shown in Figures 1 and 2, is the forerunner of a new type of ocean-going platform which promises to provide an order-of-magnitude improvement in motion reduction over conventional monohulls, as well as more deck space and internal volume and much greater speed in rough water. The SSP(1) was designed and developed by the Naval Undersea Center (NUC) to act as a work platform for NUC and to prove the new twin-hulled semisubmerged concept.

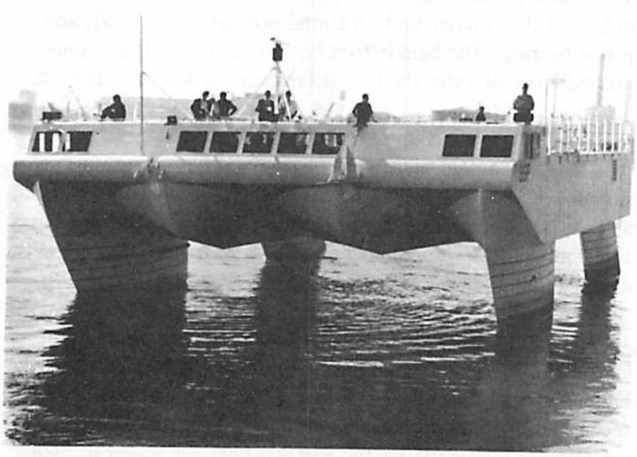

Figure 1. SSP underway.

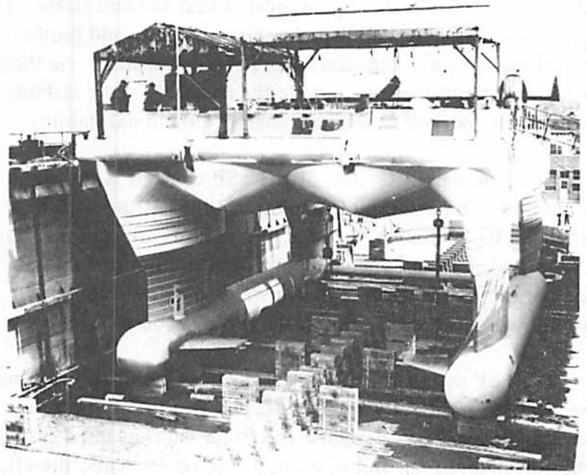

Figure 2. SSP in dry dock.

The SSP design was based on the S^3 (Semi-Submerged Ship) Concept.(2-4) The SSP is one of several types of small waterplane area twin-hulled (SWATH) craft. In 1972, about the time when construction began on the SSP, the Navy became more interested in this general type of design and initiated an overall SWATH program centered at the Naval Ship Research and Development Center (NSRDC) to conduct research and development leading toward future SWATH ships for the Navy.

Future SWATH ships may be of any size but are envisioned primarily in the range of 500 to 5,000 tons to act as destroyers, V/STOL and STOL carriers, sonar and surveillance craft, weapons carriers, patrol craft, hospital ships, and oceanic research vessels. SWATH ships should be less costly than Surface Effect Ships (SES) or hydrofoil craft and should be a better hull form on which to mount sonar systems and from which to launch aircraft.

The SSP is the first large manned model of a SWATH-type ship and represents an important step forward in demonstrating the general concept and verifying the design theory. The SSP is 89-feet long, 46-feet wide at its midsection, 32-feet high, and has an expected top speed of 25 knots with about 30 tons of payload and fuel. The structure of the SSP was designed with a large

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*The SSP was sponsored by Dr. J. Lawson, Director of Naval Laboratories, who was first assisted by Rear Adm. J. Langille and Comdr. W. Filkins and later by Capt. D. Keach in program management. The basic concept of the SSP was invented in the early 1960's by Dr. T. G. Lang who introduced the idea at NUC in 1968. The actual SSP design was initiated in 1970 following 1½ years of research sponsored by Dr. William B. McLean, technical director of NUC which was then under the command of Capt. C. Bishop and currently under the command of Capt. R. H. Gautier.

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margin of safety to help insure its integrity under extreme rough water conditions.

Design of the SSP features two parallel 6½ foot diameter torpedo-like hulls which support an above-water cross structure by means of four vertical surface-piercing struts. Two controllable canard fins are located near the hull bows and a cross stabilizing fin with controllable flaps is located near the hull sterns. The fins provide dynamic stability, damping, and trim and motion control over heave, pitch, and roll. The vertical struts, via their displacement and spacing, provide the necessary static stability in heave, pitch, and roll as well as dynamic directional stability.

The new design feature of the SSP concept is the combination of submerged hulls and streamlined struts with a stabilizing fin or fins at the rear; the canards are optional but serve to improve the dynamic damping of motion and aid in trim and motion control. Without stabilizing fins, pitch instability would occur in calm water at high Froude numbers.

The SSP design form was based on a combination of model tests and theory. Early in the SSP program, a 5-foot radio-controlled model was designed to obtain data on the dynamic behavior, model drag and hydrodynamic coefficients, the effect of wind and waves, and to simulate the results of control surface failure, hull flooding, towing, and anchoring of the SSP. The radio-controlled model tests revealed no critical dynamic problems. The largest motion occurred in following waves. Experimental and theoretical results show that the SSP should operate well under all conditions through sea-state four and into sea-state five. Several computer programs were developed to predict the motion, stability, control, drag, hydrodynamic load, and trim characteristics.

II. SSP Design Summary

Design of the SSP, shown in Figure 3, began at NUC in March 1970.* The submerged hulls and struts of the SSP are made of high tensile steel, and the cross structure is aluminum. Propulsion is provided by two gas turbines located in the cross structure that drive controllable and reversible pitch propellers through novel four-tier chain drives located in the aft struts.** Heading control is provided by twin rudders at high speeds and differential thrust at low speeds. The rudders and movable control surfaces are hydraulically powered. Provision for later adding automatic motion control is incorporated in the design.

A center well, which measures 12.5-feet wide by 23-feet long, permits the handling of a variety of small research submersibles and other types of undersea equipment.

The submerged hulls are designed for interchangeable nose sections: a transparent acrylic dome for underwater observation, special sonar domes, and steel domes for normal use. The front of one lower hull will be outfitted with an acrylic hemisphere

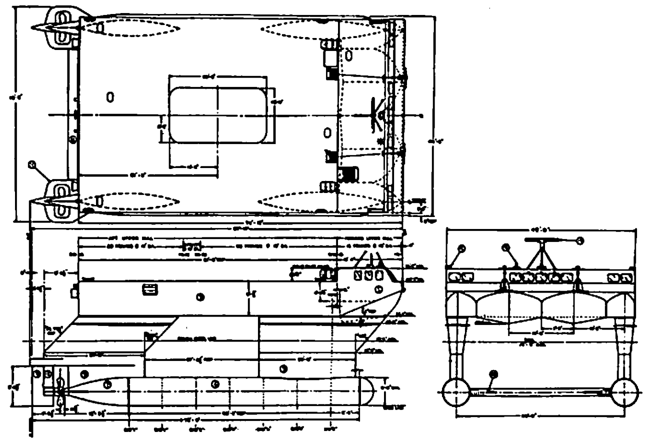

Figure 3. SSP dimensions.

casting that measures 78-inches in diameter, is 6-inches thick, and weighs 5,000 pounds. Other acrylic windows in the struts below the waterline allow the SSP's control surfaces and propellers to be viewed while underway.

In addition to the forward section, each submerged hull is divided into six 2000-gallon ballast tanks and an aft tailcone. The forward three tanks each contain a 1000-gallon rubber fuel container which separates the turbine fuel from the ballast water. The next three tanks aft are designed to contain ballast water only, and the tailcone section contains the propeller shaft and thrust bearing. The ballast/trim system on the SSP uses compressed air to dewater the ballast tanks and external hydrostatic head to flood them.

The SSP design successfully passed a safety review in the summer of 1972 conducted by the Naval Ship Systems Command and the Naval Ship Engineering Center (NAVSEC). Also, additional model tests† conducted at NSRDC verified the basic NUC design and provided supplementary data.

The SSP was constructed at the Coast Guard Shipyard in Curtis Bay, Maryland, beginning in June 1972. Launching of the basic platform took place on 7 March 1973, when it was christened "SSP Kaimalino" meaning calm-water in Hawaiian. Following a period for outfitting, the SSP was operated under its own power for the first time on 25 October 1973. After completing a series of acceptance trials, the SSP will begin a series of several months of verification trials to confirm the basic design theory. The SSP verification trials will be conducted as part of the SWATH program as a step in developing larger future SWATH

*The SSP external design and hydrodynamics was led by Dr. T. G. Lang and Dr. D. T. Higdon with assistance from C. R. Nisewanger, Dr. R. B. Chapman, and others. The mechanical and structural design was managed by Dan Hightower from the NUC Hawaii Laboratory with A. T. Strickland acting as chief design engineer. The bulk of the detailed design and structural design was performed by Pearl Harbor Navy Shipyard personnel under the direction of Cdr. C. Kreitner. The construction phase and attendant design work was managed by H. O. Porter from the NUC Hawaii Laboratory.

**The propulsion system was designed by W. Simmons of the Naval Air Engineering Center with partial sponsorship from the Naval Air Systems Command provided through R. Krida.

†Sponsored by the Naval Ship Systems Command.

ships. The verification trials plan was developed jointly by NSRDC, NAVSEC, and NUC. The first set of these trials is scheduled for the east coast near the NSRDC Laboratory at Annapolis, and the second set will be conducted near the NUC headquarters at San Diego.

III. Selection of Hull, Strut, and Fin Configurations

Underwater Hulls

The hulls provide 67 percent of the displacement and are submerged to a centerline depth of 12 feet (1.85 diameters) in order to reduce hull wave drag, reduce motion in waves, reduce cavitation susceptibility, and to help keep the propellers and sonar (if hull mounted) from emerging between waves. However, travel at reduced submergence may be preferable in calmer water since the net drag is less when draft is reduced because strut drag reduces more than hull wave drag increases.

The hull cross sections are circular in design to better structurally withstand the depth pressure, which is one of the critical loads. Also, a circular cross section provides the minimum wetted surface perimeter per unit of cross sectional area. A flattened elliptical shape was also considered since it would provide less draft and less hydrodynamic side load in waves, but it was rejected because it was heavier and more expensive to manufacture. Rectangular cross sections have been used for some of the submerged hulls on drilling rig semisubmersibles, but they tend to be heavy and produce greater drag.

A hemispherical nose was selected as being less costly and lighter in weight than a more streamlined nose, especially since the advantage of the streamlined nose in providing slightly more laminar flow is minimal. Theory and experiment show that the net integrated pressure drag of any reasonable nose shape is essentially zero as long as the boundary layer does not separate. If the speed were significantly greater, a more streamlined nose might be needed to eliminate cavitation. The wave drag does not vary appreciably with nose shape.

The tailcone shape is not critical if it is sufficiently long and adequately streamlined to prevent boundary layer separation. The SSP tailcone is 2.5 diameters long, if extended to a point. A computer analysis* showed that a cusp-shaped section was needed at the tailcone-to-propeller-shaft junction in order to prevent local boundary layer separation.

The hull length/diameter ratio is 10.8 and resulted from a compromise of several factors. A smaller ratio tends to reduce structural weight whereas a larger ratio tends to reduce hull wave drag, provides a greater submergence depth ratio, a greater gap between front and aft struts, and helps to increase the longitudinal metacentric height.

Cross Structure Bow Shape

Seven different bow shapes were tested. A 20 degree flat bow, a 30 degree flat bow, a 30 degree flat bow with a small center keel added, a four-pronged wedge-shaped bow, a larger single bow added to a 20 degree flat, a double bow with chines attached to a 20 degree flat, and a well-faired double bow without chines attached to a 20 degree flat.

Most of the tests on bow impact were made in the Off-Shore Technology Inc. Seakeeping Basin at Escondido, California. Tests were conducted in simulated 15-foot high, 225-foot long head waves. This wave is the significant wave height for sea-state 6; by using this wave height, it was found that the model in head seas would impact each wave.

The results indicated that the well-faired double bow mounted on the 20 degree flat section produced the smallest vertical and horizontal accelerations and the least amount of forward and sideward splash. The flat bows produced the largest vertical and horizontal accelerations and the largest splash at impact.

Struts

The fore and aft struts at the waterline have respective chordlengths of 25.5 feet and 24 feet with respective thicknesses of 3.8 feet and 3.6 feet. The struts are lenticular in cross section. The selection of two struts per side for the SSP, rather than one or three, resulted from many considerations:

1. A one-strut-per-side design would require more waterplane area to make the platform statically stable in pitch.

2. Early model tests[5,6] indicated that separating the waterplane area as far as possible toward the forward and aft ends of the craft significantly reduced platform motion in following waves which is the worst motion condition.

3. Evidence** indicated that the hydrodynamic sideforce, platform motion, and bottom impacts increase significantly in beam waves if the gap between the fore and aft struts is eliminated as in a one-strut-per-side design.

4. Two struts per side permit a more independent selection of waterplane area, roll metacentric height, and pitch metacentric height. Also, more design flexibility exists with regard to possible length/beam ratios than for one- or three-strut-per-side designs.

5. Two struts per side permitted human access to the hull bow sections and also the tailcone regions, whereas a one-strut-per-side design would have been undesirably thin in these regions.

6. Model drag results[5] indicated low drag at the design speed for the two-strut-per-side case since the wave drag coefficient hump occurs at the relatively low and generally unimportant operating speed of around 10 knots. The wave drag coefficient would peak at 15 knots for a one-strut-per-side design, which is closer to the operating speed region.

7. For the same waterplane area, beam, and GM requirements, the two strut-per-side design tends to have the least wetted surface area and the least structural weight.

8. The two-strut-per-side design generally leads to a smaller waterplane area which tends to provide reduced motion in waves

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*Conducted by D. Nelson, NUC, Pasadena.

**Model test results at NUC on a model of a large floating platform.

and makes full motion control more easily achievable with small control surfaces.

The waterplane area was the leading factor that determined strut size, and it was dictated primarily by the static stability requirement in roll, i.e., metacentric height (GM) in roll. Earlier model tests[5,6] and theory indicated that the minimum GM should be about 1/4 of a hull diameter, although 3/4 of a hull diameter was much preferred. Even larger GM values might be desirable since motion in waves reduces as GM increases for the range of values under consideration.

The equation for GM in roll is:

$$GM = GB + \frac{I}{\nabla} \doteq GB + \frac{b^2 A}{4\,\nabla},$$

where GB is the distance upward from the center of gravity to the center of buoyancy, I is the transverse waterplane second area moment, b is the transverse strut centerline spacing, A is the total waterplane area, and ∇ is the platform displacement. It is seen that A reduces as the beam and b increase to maintain constant GM, which leads to reduced strut size and drag. However, the structural weight of the cross structure increases as the beam increases, so that a tradeoff exists between structural weight and drag which results from the tradeoff between beam and waterplane area for a given required GM. The required GM for the SSP was selected as 4.5 feet, and after several design tradeoff studies the transverse strut centerline spacing was selected as 40 feet. This selection dictated the waterplane area.

The strut thickness-to-chord ratios were selected as 15 percent; this was a compromise between the reduced structural weight and hydrodynamic sideload that could be achieved with thick struts, the reduced wave drag of thin struts, and the need for fairly thick struts from the viewpoint of human access.

The 14.75-foot strut height is the sum of the 6-foot clearance of the above-water cross structure and the 8.75-foot depth at the hull tops. The cross structure clearance was selected largely so that waves would clear the cross structure when the SSP was operating at top speed in sea-state 4 as well as to minimize wave impacts on the SSP when operating at reduced speeds in sea-state 5. As stated earlier, the hull depth was selected among other reasons to prevent propeller emergence in high waves. The strut height of 14.75 feet is a measure of the maximum wave height that can be negotiated without it either hitting the cross structure or exposing the hulls, assuming level flight and assuming that the SSP is dynamically trimmed with the water surface at the strut midpoint.

Spray Rails

At speeds above the strut wave drag hump, a thin spray sheet will begin to climb up the strut. This spray sheet has been experimentally investigated at NUC.[7,8] It was found that the spray produced drag on the strut primarily by increasing the wetted surface area. Also, spray impingement on trailing parts is a potential source of additional drag. Consequently, horizontal spray rails similar to those described in Ref. 7 were designed and added to the starboard struts in order to reduce both of these drag sources and permit comparison with the spray sheet on the port struts which have no spray rails.

Aft Stabilizing Foil

As mentioned above, the second area moment of the water plane area about the pitch axis must be large enough to move the pitch metacenter above the center of gravity to assure pitch stability at rest. The underwater hull alone, however, is hydrodynamically unstable underway; the destabilizing moment being proportional to velocity squared. This means that the instability of the underwater hull will overcome the hydrostatic stability provided by the struts if the speed is high enough. The SSP would become unstable (i.e., assume either a full bow down or bow up attitude depending on initial conditions) without a stabilizing foil at a speed of about 15 knots, a speed well below the design speed range. Unsatisfactory pitch trim behavior would occur at lower speeds.

A simplified single degree of freedom analysis shows that to assure pitch stability at any speed the stabilizer area must be large enough to satisfy

$$S_{stab} > \frac{\pi\, d_h^2}{a_{stab}},$$

where S_{stab} and a_{stab} are the area and lift coefficient slope of the stabilizer and d_h is the underwater hull diameter. A simulation with both pitch and heave degrees of freedom agreed closely with the above results. The SSP stabilizer foil actually chosen was several times larger than this minimum. Early model tests on this type of hull (see Ref. 4, Part II) indicated that the larger (full span) foil improved the general behavior in both calm water and waves, and it was thought that such a full span foil would also help in relieving the side loads due to waves in beam seas. Furthermore, the decision to add canard foils near the bow required more stabilizer area to offset their adverse effects on pitch stability as indicated in the simplified formula below:

$$S_{stab} > \frac{\pi\, d_h^2}{a_{stab}} + \frac{a_{canards}}{a_{stab}} S_{canards}$$

The foil chosen was similar in shape to the full-span model foil and has a 7.8 foot chord, a span from hull to hull, and a modified NACA 64-021 section. This was also considered to be the smallest foil which could be made strong enough to span the distance between the hulls.

Canard Foils

The presence of foils both fore and aft permit independent control over pitch, heave, and roll with moveable foils or flaps. Such control is useful for both manual trim and automatic motion reduction in a seaway. This degree of motion control would be unprecedented in a displacement supported craft. Control surface deflection requirements for trim and motion control are discussed in a later section.

Simulations of the vertical plane motions (pitch, heave) of a platform having only the full span stabilizing foil discussed above showed a lightly damped oscillatory motion, even at high speed. This is indicated by the period and time to half amplitude for the oscillation, as shown in Table 1. Towing tests of a similar model failed to produce oscillations as lightly damped as those in the simulation, possibly because the analysis did not include damping due to viscous or wave-making effects. The simulation indicated,

Table 1. Effect of canards on predicted period and time to half amplitude of SSP pitch-heave oscillations

	14.5 knots		23.1 knots	
	Without Canards	With Canards	Without Canards	With Canards
Period, sec	8.99	11.49	9.50	13.15
Time to 1/2 amplitude, sec	9.38	3.94	9.73	5.43

however, that addition of foils (canards) near the nose would significantly improve the damping of the pitch-heave oscillations, as shown in Table 1. Model tests showed that having foils both fore and aft greatly improved the damping of motions at rest as well as underway.

The size of the canards was selected to give the best passive dynamic behavior as estimated by simulations and is naturally considerably smaller than that of the aft stabilizing foil. Therefore, the canards were designed as individual cantilevered foils mounted on the inboard side of the hulls to avoid damage from minor collisions. The foils have a swept leading edge and a geometric aspect ratio of about 1.0. Because of the presence of the hull, the effective aspect ratio is around 2.0. The section is a modified NACA 64-015.

Rudders

The four-strut configuration chosen for the SSP was found through both analysis and model experiments to have a high degree of directional stability. Therefore, the rudders had to be reasonably effective in order to achieve acceptable turning performance. Considerable effort was made to place the rudders as far aft as possible and take full advantage of the higher velocity flow in the propeller race. The rudders were made to extend upward from the keel to a point sufficiently below the design waterline to avoid ventilation.

A free running model very similar to the present SSP configuration had a turning circle diameter of 4½ platform lengths with a 30 degree rudder deflection at full power. From a straight running speed of about 23 knots scaled to the SSP, the model slowed an equivalent 8 knots when in the steady-state turn.

IV. Propulsion System and Powering

Propulsion System

Two 2100 HP, GE T64-B, gas turbines were selected for the power plant because of their light weight and availability from NAVAIR at no program cost. The selected chain drive and propeller system is good for experimental purposes since the gear ratio can be changed easily by changing sprocket sizes and the propeller pitch can be varied quickly from 100 inches forward to 50 inches reverse. A thrust gage, torque gage, and RPM monitor have been inserted in the drive shaft system to obtain powering data. Speed is indicated by a Kenyon propeller log installed four feet aft of the nose joint on the port hull, 45 degrees up from the bottom on the outer side. A plexiglass window for TV monitoring has been installed above each propeller.

Thrust is produced by two identical four-bladed Wilkinson CRP propellers, 78-inches in diameter, 345 RPM, with an expanded blade area ratio of 0.575 and Troost B4.70 series blade sections of 0.045 thickness ratio. A five-bladed propeller would have been preferable from the vibration reduction viewpoint, but cost, hub space, complexity, and additional development time precluded its use.

Theory* provided the data for the propeller design which included the boundary layer inflow to the propellers, wake fraction of 0.24, thrust deduction of 0.10, and propulsive efficiency of 0.77. The propellers were designed to have the same diameter as the hull to make them as large as possible without excessively exposing them to damage. The use of large diameter propellers improves efficiency, and when only one propeller is operating the larger diameter reduces propeller loading and cavitation.

Powering

The experimental drag coefficients** for the 5-foot SSP model are shown in Figure 4, together with the calculated theoretical prediction(9). All coefficients have been scaled to the SSP size by correcting for Reynolds number. The theoretical prediction includes the wave drag of struts and hulls, turbulent frictional drag, the overvelocity effect caused by strut and hull thickness, surface roughness, pressure drag, and spray drag. The original drag estimates used to determine the power needed for the SSP were based upon early model tests(5) and limited wave drag theory; these estimates were about 15 percent less than those shown in Figure 4, but they were adequate for early design purposes.

The theoretical effective horsepower for the SSP is shown in Figure 5.† Notice that the added drag of the fins is relatively small in relation to the advantages and needs for incorporating them. At the continuous rating of 4200 HP, the predicted speed is 25 knots, assuming a propulsive coefficient of 77 percent.

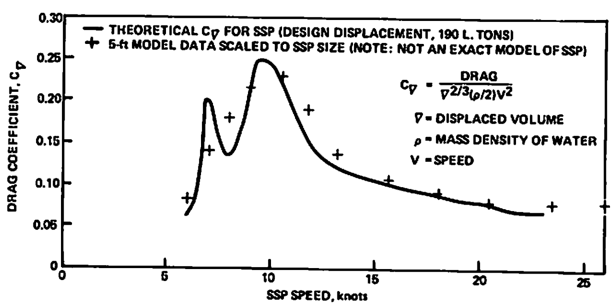


Figure 4. Comparison of theoretical and experimental drag coefficients of the SSP.

*Conducted by D. Nelson, NUC. These calculations were made for a 6-foot diameter propeller mounted on a 6-foot diameter hull prior to the final selection of 6½ foot hull and propeller diameters. The calculations were scaled for the new diameter and are believed to be reasonably accurate.

**The tests were conducted in the Lockheed Towing Tank, San Diego.

†Calculated by Dr. R. B. Chapman, NUC.

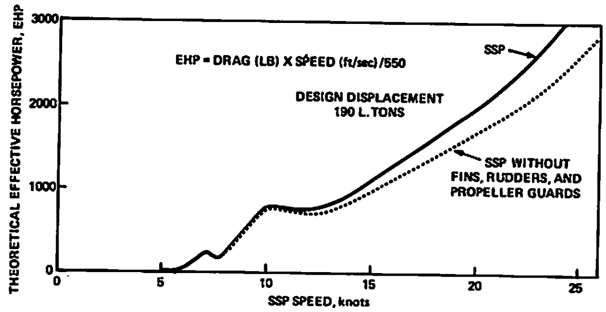


Figure 5. Predicted effective horsepower.

Greater power and speed are available for shorter periods. Power requirements reduce significantly with draft; thus, increased speed will result if expended fuel is not replaced by ballast water, if the payload is reduced, or if the SSP is dynamically trimmed to a shallower draft.

The predicted SSP speed and power compare favorably with the following reported speeds and powers for similar sized monohulls:(10) 143 tons, 3600 HP, 24 knots; 202 tons, 3200 HP, 23 knots; 146 tons, 4000 HP, 24 knots; 123 tons, 3000 HP, 25 knots. Since the SSP speed will change little in rough water while monohull speed degrades rapidly, the SSP should significantly outperform monohulls in rough water.

V. Horizontal Control Surfaces

The main reasons for having the horizontal foils controllable are:

(1) to supply heave force and pitching moment required to trim the ship throughout its speed range;

(2) to allow a dynamic change in draft at moderate to high speeds;

(3) to provide roll-turn coordination capability; and

(4) to counteract wave forces in response to command from either an automatic motion control system or a quick-response manual control system.

The need for trim correction throughout the speed range can be seen by looking at the predicted sinkage and pitch trim over the upper speed range with fixed foil incidence, as shown in Figure 6. These results were based on trim forces and moments and stability derivatives measured on a 10.5-foot SSP model at NSRDC.*

A number of requirements were placed on the control surfaces. They must be able to maintain zero pitch and design draft throughout the speed range in calm water. Also, there must be sufficient control to lift the SSP from design draft to the onset of broaching of the lower hulls at high speed. This would allow

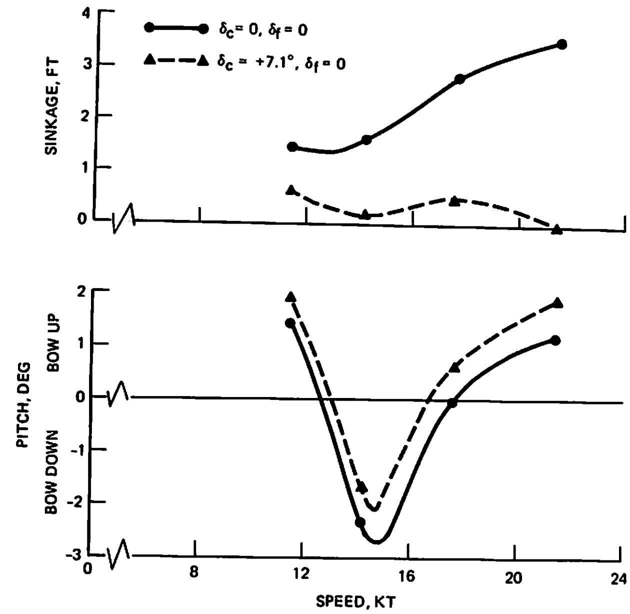


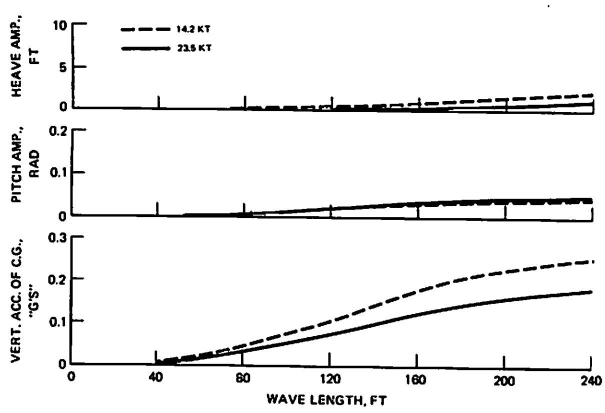
Figure 6. Predicted SSP sinkage and pitch trim for fixed control settings.

easy adjustment to best draft for a given sea condition and rapid compensation for a change in load such as aircraft takeoff or landing.

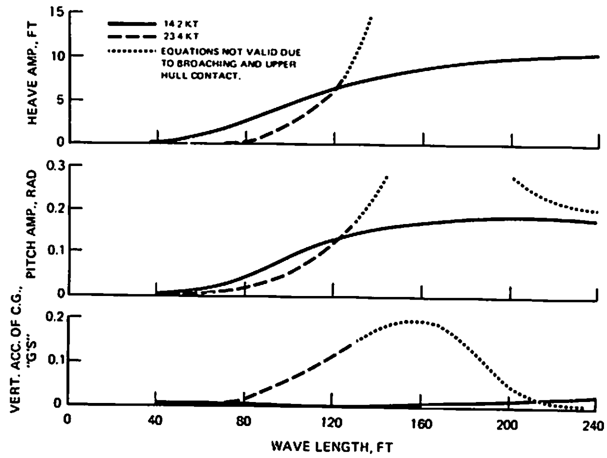
Conventional displacement hull vessels usually tend to heel out of a high-speed turn causing the gravitational force to add to the centrifugal force which acts on objects to move them along the deck. Free-running model tests showed that the SSP would heel into a high-speed turn actually somewhat more than necessary for the deckwise components of gravitational and centrifugal force to cancel. It was found that a very modest differential deflection of two half-span quarter chord flaps on the aft stabilizing foil was adequate to produce either perfectly coordinated turns or turns with zero heel. Thus, the requirement to provide roll-turn coordination was easily met within the assumed requirements for motion control.

The most demanding requirement was that the control surfaces be capable of completely cancelling motions in waves of length-to-height ratios of 20 in waves up to 10 feet high at moderate to high speed. This was a fairly ambitious goal but computer simulations of SSP motions in head and following waves with an idealized pitch and heave control showed it was possible to achieve providing that the canards were all movable. A 25 percent chord flap was adequate for the aft stabilizer foil. Predicted motions of the uncontrolled SSP at medium and high speed are shown in Figure 7. The control surface motions required to completely eliminate pitch and heave at these speeds are shown in Figure 8. It was assumed that the requirements imposed by head and following seas would also take care of beam and quartering seas. Rudder

*Tests performed at NSRDC on a 1/7.8 scale model in the spring of 1971.



(a) Head Waves



(b) Following Waves

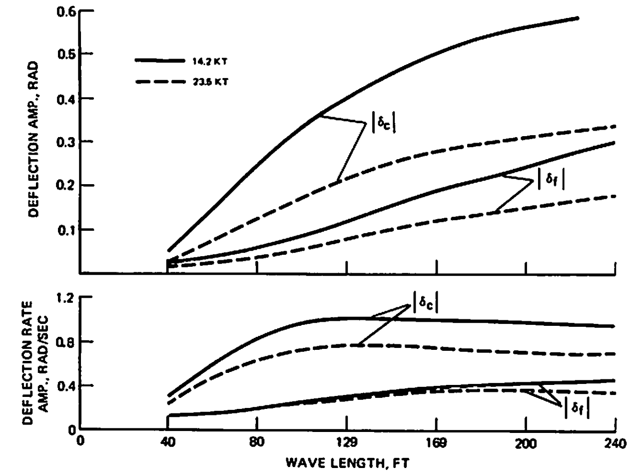
Figure 7. Motions of uncontrolled SSP in regular waves of height-to-length ratio 1/20.

deflection and rate requirements were assumed to be similar to those for the flaps.

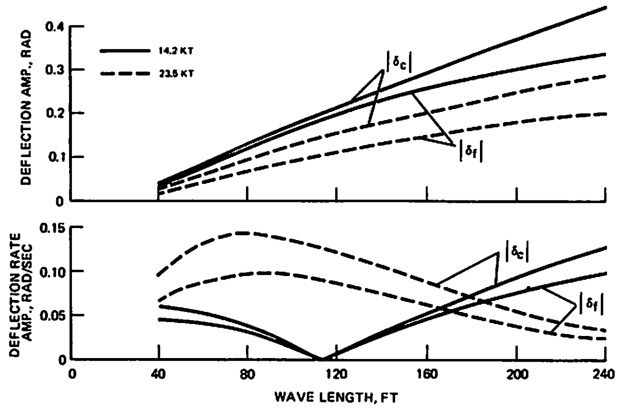
VI. Critical Hydrodynamic Loads Estimates

One of the major concerns early in the SSP design was the determination of design side loads on the lower hulls and struts because of the moment they could produce at the juncture of the slender struts and the upper hull. The primary source of these loads are high speed turns and waves. Assuming the worst vertical center of gravity location and heel angle, entry into a turn at high speed was estimated to produce a load acting on one side as high as 20 percent of the total SSP displacement.

The worst lateral wave induced loads were assumed to occur while running parallel to the wave crests (beam seas) at top speed. It was observed that a free running model had a relatively small amount of roll in beam waves which suggested that design loads could be estimated with a simplified single degree of freedom simulation allowing sway only. Sway motion was considered to be the primary mechanism of relieving the loads imposed by the



(a) Head Waves



(b) Following Waves

Figure 8. Canard and flap deflection and rate amplitudes for perfect stabilization in waves of height-to-length ratio 1/20.

waves. The loads were assumed to be the sum of two sources: (1) wave loads on the platform not free to move in sway, and (2) loads on the platform due to induced sway motions. The loads for each source were computed assuming virtual mass, pressure gradient, and circulatory lift forces which would occur in the flow field of the undisturbed wave or due to the platform's translational motion. Free-surface effects such as wave diffraction and reflection as well as unsteady rotational flow effects were not included.

Figure 9 shows the estimated amplitude of side load and lateral acceleration as a function of wave length for a wave height to length ratio of 1/10. The same model used with a sea-state 5 wave spectrum gave the results shown in Table 2.

Table 2. Predicted Side Load Response to Sea-State 5

(Displacement Δ = 190 long tons)

	Zero Speed	High Speed
Ave 1/3 highest	.216Δ	.280Δ
Ave 1/100 highest	.361Δ	.467Δ

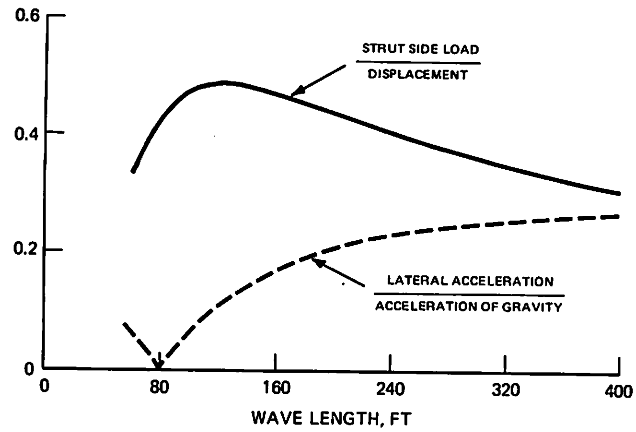


Figure 9. Estimated strut side load at 23.5 knots in beam waves of height-to-length ratio 1/10.

The design side load used was 0.5Δ. This does not allow for the possibility of superposition of high-speed turn loads, but a safety factor of at least 2.0 in the structural design should take care of this eventuality.

The normal hydrodynamic loads on the aft stabilizing foil were also considered critical because of the large span. These loads could be generated by waves or flap deflections. The largest loads from waves were assumed to occur at high speed in head waves. These loads were computed from a dynamic simulation of pitch and heave degrees of freedom in regular head waves and the results combined with a standard sea-state spectrum. For sea-state 5 the results were an average 1/3 highest load of 0.08Δ and an average 1/100 highest load of 0.13Δ.

An accidental hard-over deflection of the full span flaps at high speed was estimated to produce a load of about 0.63Δ. This was taken as the design load.

Canard loads were computed in a similar manner, giving a design load of 0.15Δ. Upper hull torsion loads were estimated for a slam on one side of the bow and also for opposing differential canard and flap deflections at high speed. The worst hydrodynamically-imposed torsion load would be equivalent to about 25 long-tons applied upward at each of two diagonally opposed corners and downward at the other two. Actual design torsion loads were determined by an assumed drydock situation supporting the weight of the ship under diagonally opposed struts. Rudder loads were estimated for sudden full deflections at high speed giving a load of 0.15Δ each.

VII. Reflections on the Hydrodynamic Design

The design of the SSP began early in the research and development phase of this new type of concept. Although the 190-ton SSP has already been designed, constructed, and operated, basic SWATH research is continuing on various aspects of resistance, motions, control, structure, and sea loads. Although it is still too early for a comprehensive evaluation of the hydrodynamic design of the SSP, many things have been learned during the detail design, construction, and early operational periods through analysis, model tests, and the design process itself.

Results from initial SSP operations indicate that the SSP has thus far performed as predicted. These operations have been limited to calm water and shakedown runs. Speed log results indicate that the SSP has achieved its design speed of 25 knots. High-speed turns have been made with the expected positive and fast response to rudders. Deflections of the canards and flaps provided strong dynamic control over heave, pitch, and roll. Also, the craft was easily controlled in yaw during single engine operation runs.

The reasons for selecting four struts, an aft-mounted pitch stabilizer, canard fins, the cross-structure bow shape, and the aft-mounted rudders remain valid. The selection of the shapes and sizes of these components also remains current, as does the desirability of an automatic control system to reduce motion in large waves.

The theory developed early in the SSP design phase for pitch stability and damping, motion in head and following waves, most of the hydrodynamic loads, drag, automatic control effectiveness, and control forces is still considered to be generally within engineering accuracy. The early towed and radio-controlled model tests provided the required roll metacentric height, the determination of heel due to wind and waves, hydrodynamic coefficients, turn rates and heel in turns, trim settings, natural frequencies and damping, motion in waves, control effectiveness, and roll/yaw/pitch effects.

In regard to changes, free-running model tests have shown that in very rough water at high speed, upper hull slamming can be very severe while lower hull broaching is a relatively mild phenomenon, except for possible problems from propeller ventilation. This indicates that the design waterline should be moved downward on the struts from its current position to at least midway between the upper and lower hulls to minimize slamming while still avoiding excessive propeller ventilation. At high speed the mean waterline is largely determined by the dynamic forces generated by the control surfaces, so there should be no problem with running the SSP at the best waterline.

One of the original justifications for the full span stabilizer was that it would help the rear struts carry the beam-sea side loads and hence lighten the structure. As it happened, the very large design loads on the foil and the large span resulted in a foil design which may have more overall structural weight than two smaller alternative cantilever foils. Computer simulations indicate that two cantilevered foils totaling about 60 percent of the existing aft foil area would reduce the motions of the uncontrolled platform in following seas without affecting head-sea behavior. The reduced wetted area would reduce drag as well; however, calm water trim changes would increase. On the other hand, since the smaller foils must be cantilevered, it is not clear that any great weight savings would occur because of the heavier support structure in the hulls as well as the heavier aft strut structure. Experimental data on SSP behavior with smaller foils is still too sparse to warrant a design change at this stage.

Side loads have been measured on a model related in configuration to the SSP at rest in regular beam waves at the Lockheed Ocean Laboratory in San Diego. The side loads were 50 percent higher for the model tests than those predicted by the simplified method used in the SSP design. The waves in the model tests had height-to-length ratios of 1/40 and 1/20. On the other hand, predictions for side loads on the 10.5 foot NSRDC model with wave lengths of twice the beam agreed well with actual measurements. Wave load theory has been developed at NSRDC[11] which includes diffraction effects, and work there has shown these effects to produce an important part of the side loads on one-strut-per-side SWATH ships. If the SSP side loads are 50 percent higher than the design loads, the slack will have to be taken up by the structural design safety factor of 2.0 or more.

The SSP was originally given a heavy overall structural design to assure its integrity under all test conditions. Large factors of safety were used on top of what are believed to be liberal estimates of maximum loads. Strain gage data to be obtained during future operations will likely yield information that can be used to reduce the structural weight on future designs through structural optimization. Also, if the craft were made entirely of aluminum it should lead to a significant weight reduction.

Work at NUC has shown that the use of aircraft-type servo tabs on flaps and on the all-movable canards could greatly reduce the power required for rapid actuation. Although this is not a critical problem on a craft as small as the SSP (which can produce up to 160 horsepower for control hydraulics), control power reduction would be essential if active motion control were to be used on larger ships of this type.

Much work has been done on SWATH ship technology since the SSP was designed.[9-16] Although the SSP was not designed as a "scale model" for future SWATH ship designs, the engineering test programs of NSRDC and NUC should provide valuable correlation of theoretical methods, model tests, and full scale results for powering, motions, and sea loads of SWATH ships. In addition, the SSP can be used to explore the applications which can best take advantage of the unique wide deck configuration and the superior motions and powering performance which can be provided by this type of craft in a seaway.

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