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S^3—New Type of High-Performance Semisubmerged Ship

The S^3 semisubmerged ship concept consists basically of two parallel torpedo-like hulls, submerged to a depth of about two diameters and attached to an above-water platform by means of four vertical struts. Horizontal fins and control surfaces attached to the hulls provide dynamic stability and permit full automatic control over pitch, heave, and roll. The anticipated advantages of the S^3 over conventional ships are greatly improved seaworthiness, high-speed potential, large internal volume and deck area, controllability, and many aspects of its unusual hydrodynamic form. The S^3 concept appears to be most applicable to small ships (100 to 15,000 tons) having missions associated with the use of sonar—the handling of aircraft, weapons, or submersibles—and for missions requiring a high degree of seaworthiness and stability.

Introduction

It would be desirable to reduce the size of ships as a means of reducing their cost and increasing their operational flexibility. However, if the size of conventional ships is reduced, their motion in waves would become excessive, their wave-making resistance would increase, they would become even more volume-limited, their ability to carry a given topside weight would reduce, and helicopter and sonar operations in rough water would have to be curtailed in many instances.

A new type of semisubmerged ship called the S^3 is presented here which shows promise for solving these problems. Relative to conventional ships having the same displacement, the S^3 should provide:

1 Greatly improved seaworthiness at all speeds, including at rest
2 Higher speed and greater maneuverability
3 Improved sonar, towing, aircraft handling, and weapon-launching capabilities
4 Lower wave drag at cruise and top speeds
5 Increased topside weight capacity and deck space
6 Greater propulsive efficiency and reduced cavitation
7 Near-level flight in most sea states by using control surfaces
8 Greater burst-speed capability, since wave drag is negligible at higher speeds
9 Cost reduction through modular design and geometric simplicity of components
10 Short development period, since existing components can be utilized.

The interest at the Naval Undersea Research and Development Center (NUC) in semisubmerged ships began in 1968. The need arose in one of the NUC undersea systems for a small, inexpensive support ship for an unmanned undersea vehicle and one which could travel as fast as large naval ships in rough seas. None of the current new ship concepts was acceptable, each for different reasons. Some of the advanced concepts are described in reference [1].[1] Some of the previously proposed semisubmerged ship designs appeared to come close to satisfying the need, but they suffered from lack of stability at high speed. As a result, a new design of a semisubmerged ship was proposed at NUC called the S^3. A study of the S^3 was funded in the Fall of 1968 by Dr. McLean under the Center's IED program.

A preliminary analysis[2] indicated that the concept had sufficient technical merit to warrant further work. A series of tow-tank tests on 5-ft models was conducted to investigate such critical problems as dynamic stability, the response to waves, the control forces required to provide level flight in waves, and the effect of changes in configuration on drag and behavior. These tests were conducted in the Convair, General Dynamics Towing Tank in San Diego during August and September 1969. The test results showed no technical barriers; so a more comprehensive study[3] was conducted, consisting of both a mission analysis and a technical analysis. The results (reference [2]) showed a continuing promise to not only satisfy the original need but to satisfy many other types of naval and non-military needs. As a consequence, a 5-ft radio-controlled model was constructed, and the design of a 190-ton version[4] was begun. More recently, additional

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[1] Numbers in brackets designate References at end of paper.
[2] Lang, T. G., "A New Look at Semisubmerged Ships for the Navy," Internal NUC report, TN 251, May 1969.
[3] Funded by ONR 462, 463, NAVAIR 303, and NAVSHIPS 03411.
[4] Funded by NAVMAT 03L.

naval utility studies have been conducted, and a new series of tests completed on an 11-foot model[5] of the 190-ton version of the S^3 at the Naval Ship Research and Development Center. Most recently, a 3000-ton high-performance S^3 was studied for use in naval operations; the results indicated that it might be the best solution for many types of naval missions.

Description of the S^3

The S^3 design concept (Fig. 1) consists basically of two parallel deeply-submerged torpedolike hulls which are each attached by a pair of hydrofoil struts to a platform located well above the water surface. Horizontal hydrofoils are attached to each of the torpedolike hulls at their bows and sterns for providing dynamic stability and to fully control pitch, heave, and roll.

The design approach to the S^3 can be described while referring to Fig. 1. The primary buoyancy is supplied by two streamlined hulls submerged to a depth of approximately two diameters. The wave-making resistance and wave-induced forces are much less on such hulls than on conventional ship hulls. A wake-adapted propulsor, such as a propeller or pumpjet, is placed at the end of each hull to utilize the boundary layer inflow for increased efficiency.

Two vertical, surface-piercing, buoyant struts are attached to each hull. These struts provide hydrostatic stability in pitch and heave resulting from their waterplane areas and spacing, as well as hydrodynamic stability in yaw due to their behavior as hydrofoils. Incorporation of rudders in the struts provide good maneuverability due to the fact that a composite strut-rudder combination acts like a rudder. Some S^3 designs may utilize only aft rudders for simplicity. Placement of rudders in the propeller slip-stream tends to provide additional rudder force. Other S^3 designs may utilize only forward rudders, as in some hydrofoil boats, to reduce sway response in waves. Still other S^3 designs may use both forward and aft rudders to obtain full control over sway and yaw.

A submerged hull by itself is hydrodynamically unstable in pitch, the destabilizing effect being proportional to velocity squared. Since the hydrostatic pitch stability provided by the struts is independent of speed, the combination will become unstable above a certain critical speed which depends upon the configuration. Therefore, a horizontal tail stabilizing fin (or fins) has been incorporated to provide pitch stability at high speeds. This fin also provides increased roll and pitch damping.

The two hull-strut systems, when placed sufficiently far apart and attached rigidly to the superstructure, provide stability in roll. Hydrostatic roll stability is achieved through differential heave of the two hull-strut systems, and roll damping is provided by the two submerged hulls and horizontal tail fin.

[5] Funded by NAVSHIPS 03411.

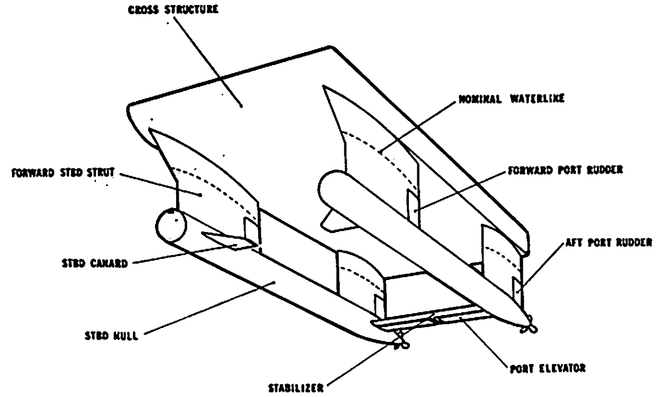


Fig. 1 Sketch of the S^3 concept

The incorporation of control flaps in the horizontal fin and addition of small controllable horizontal canard surfaces on the forward part of the submerged hulls provides the means for very effective control over response to waves in heave, pitch, and roll.

The relatively low wave drag of this configuration allows efficient high-speed operation of small ships and appears to be best suited (performancewise) to combinations of size and speed lying between hydrofoil boats and conventional ships. Selection of strut size, lateral and longitudinal spacing, waterplane area, and horizontal fin sizes and locations allows virtually independent selection of pitch, heave, yaw, and roll response. In general, for low response to waves, low natural frequencies are desired. Low frequencies are obtained by the combined effects of small waterplane cross-sectional areas and the large radii of gyration in pitch and roll inherent in this relatively dispersed configuration. Therefore, this configuration should provide excellent operational characteristics, whether controlled or not.

Basic Features and Applications

The general results of studies to date indicate that the S^3 may be superior to other hull forms for a variety of naval (reference [2] Part VII) and nonmilitary applications, such as small helo/VTOL carriers; missile platforms; patrol, escort, and surveillance ships; coastal patrol; search and rescue; oceanic research; submarine support; floating hospitals; fishing boats; cargo ships; and passenger or cruise ships. The most useful sizes appear to lie between 100 and 15,000 tons. This is the range where the improved seaworthiness and performance are most significant.

In regard to naval applications, since the life span of a ship is long compared to foreseeable naval missions, it appears desirable to design mission flexibility into the S^3 configurations and make use of modular design components. As an ocean-going tugboat, an S^3 could be quite small and yet tow either large surface pods or submerged cargo pods. Joining several S^3s together to form a stable ocean platform also appears feasible.

From the viewpoint of engineering feasibility, the S^3 looks very promising. Model test results (reference [2], Part II) indicate that wave drag is negligible at cruise and top speeds, so the ships can have relatively good burst speed capability. The drag increases very little in waves relative to conventional ships, and the seaworthiness appears to be much improved, both at rest and underway. Tests show that an S^3 can operate with one engine with negligible yaw and essentially no drag increase.

The most practical power plant (reference [2], Part V) for moderate to high speed S^3 designs is the gas turbine. These can be placed in removable tailcone modules. Multiple turbines and variable pitch propellers provide performance flexibility. Although pumpjets would provide the most quiet operation, even propellers would operate more quietly on an S^3 because of their increased depth and the improved boundary layer inflow conditions. Twin propulsion systems provide increased reliability and minimize the effects of damage to one hull. Operation with one engine provides extended range because one turbine at full power is more efficient than two turbines at half power.

The ship appears to have a very high potential for use as a sonar platform (reference [2], Part VI). The improved stability, wide hull spacing, and deep submergence provide greater sonar resolution, less cavitation, and quieter operation.

The structural weight to total weight ratio of an S^3 is larger than that of a conventional ship and will vary depending upon the size and mission. An estimate (reference [2], Part IV) places the value around 0.50 to 0.60 for steel; recent estimates place this value around 0.40 for aluminum, which appears to be the most attractive material. Compared to certain volume-limited ships, however, the total structural weight of even an all-steel S^3 might be lower. The reduced cost of simple geometric components and use of structural modularization may more than offset the structural weight penalty. Also, the greatly increased deck area, greater topside load carrying capability, and larger internal volume should help offset any penalties. Placement of the cross structure well above the water level reduces wave impact loading; furthermore, the use of a relatively small waterplane area greatly reduces structural loads and motion in waves, since the change in buoyancy due to a wave is relatively small.

There appear to be no fundamental dynamic and control problems (reference [2], Part III). An S^3 will be stable and seaworthy when at rest or underway, either with or without an automatic control system. Model test results and analyses show that the addition of an automatic control system would permit the ship to operate nearly level in unusually high sea states. For example, results indicate that a 3000-ton ship should operate nearly level through sea state 6 and well into sea state 7. Such an improvement would significantly improve human performance and aid in equipment operation (reference [3]).

The location above water of the personnel, living quarters, aircraft, and weapons, and below water of the propulsion, fuel, sonar, and ammunition provides good space utilization, simplifies access, lowers the center of gravity, and reduces the effects of damage to either the above-water or below-water portions. The increased deck area, speed, and stability make an S^3 well-suited for use by helicopter and other V/STOL aircraft. The box-like cross structure provides easy access from the top, sides, back, and bottom and may lead to greater operational flexibility. A central opening may be placed in the bottom of the upper platform for handling submersibles or small boats. The unusual configuration is also well-adapted for towing submerged objects. A retractable, pivoted, towing arm can be lowered from the platform and locked into the aft stabilizing fin so the tow force is applied along the thrust plane.

The many advantages of an S^3 design, however, must offset its disadvantages by a considerable margin for it to be seriously considered for future use. All new design concepts which promise a large number of improvements generally have some disadvantages which prevent them from becoming a universal cure-all. The possible limitations of an S^3 are: (*a*) the structural-to-total weight ratio may be greater than for conventional ships, (*b*) the increased beam may provide problems in docking or drydocking, (*c*) more precise static trim is needed, and (*d*) the draft of the larger versions may be too great for certain harbors unless means are incorporated for reducing draft.

Other Types of Semisubmerged Ships

Although semisubmerged ships are not new, they have received only limited attention. One of the first single-hulled semisubmerged ships was invented in 1880 by Lundborg (Patent No. 234,794). The first multiple-hulled design appears to have been invented by Blair in 1929 (Patent No. 1,753,399) and is somewhat similar to the more recent MOHOLE platform (reference [4]). A more streamlined twin-hulled design was proposed in 1946 by Creed (Patent No. 2,405,115) and consists of an above-water cross structure attached to one long, streamlined strut on each side, which are in turn attached to a pair of torpedolike hulls. In 1959, Boericke (reference [5]) in NAVSHIPS proposed the "shark form" single-hulled semisubmerged ship, which is an improved, modern version of Lundborg's design. Recently, independent of the S^3 program which began in 1968, Leopold of Litton Systems (reference [6]) proposed the Trisec, which somewhat resembles the Creed design but is a much-improved design and directed toward larger ships. Another twin-hulled design consisting of a cross structure, four struts, and two torpedolike bodies was proposed by an MIT student in a class project (reference [7]). In 1969, the Netherlands Offshore Company launched a 1200-ton, 8-kn, twin-hulled semisubmerged dredging/drilling rig called the Duplus (reference [8]). In a recent program, after interest picked up in semisubmerged ships, the Naval Ship Research and Development Center has explored a series of semisubmerged catamaran configurations with one long strut on each side called "modcats." These are somewhat like the Litton Trisec and the Creed designs.

The S^3 differs from the other semisubmerged ships in many respects, some of which relate to its general design form—such as hull and strut geometry and depths—and the fact that it has stabilizing fins, a set of horizontal control surfaces, and an automatic control system driving the control surfaces to fully control the ship in pitch, roll, and heave. Analysis indicates that none of the preceding semisubmerged ships designed for the same topside load and speed will have as low a drag as the S^3; furthermore, it is doubtful that any of the earlier configurations will be stable at the cruise and top speeds of the S^3. Also, the S^3 should be more seaworthy and far more controllable than preceding types of semisubmerged ships.

Technical Analysis

Geometric Form. The form of the S^3 design resulted from the optimization of many factors, including drag, stability and damping, motion in waves, controllability, structural strength, and potential cost.

The combination of deep draft and the spanning stabilizing fin (or one fin on each hull) provides good stability in both calm water and waves at all speeds. The wide strut spacing provides good static stability in roll and permits large topside loads to be carried. The horizontal surfaces give excellent damping in heave, pitch, and roll so that resonance problems in waves are eliminated or greatly reduced. The various rudder options provide excellent maneuverability and control over yaw and sway in waves. The use of aft rudders located relatively low have been shown by model tests to provide an inward bank in turns. The coupling of rudders to canards or flaps will provide nearly any desired combination of bank and turn rate. The canards and flaps should also provide full control over pitch, heave, and random roll.

Struts with lenticular cross sections having constant curvature are simple to manufacture, provide low drag at the design speed, offer adequate strength, and provide sufficient cross sectional area for both human access and air intake and exhaust for gas turbines if located in the hulls. The canards and stabilizing fin have airfoil cross sections, however, since drag is somewhat lower for airfoil sections than for lenticular sections when fully submerged. In regard to new types of control means, one possibility is to exhaust air through holes in the stabilizing fin, forward horizontal control surfaces, and in the vertical struts for quick and very efficient control (reference [9]). Such a control means is relatively new, however, and would require some exploratory work before being applied.

Although propellers may be used for the propulsors at speeds up to 30 or 40 kn, it is likely that pumpjets, base ventilated propellers, or superventilated propeller blades will be needed at higher speeds. A general discussion of hydrofoil design pertinent to base vented or superventilated blade design is presented in reference [10].

In regard to the strut design, their upper portions, especially the above-water portions, can be designed with a bluff cut-off trailing edge to provide greater strength and greater displacement. The increased drag of such base-vented sections can be relatively small (reference [11]). Alternatively, the upper portions of the struts could be enlarged while maintaining the same lenticular shape.

The hulls are cylindrical to reduce cost and are submerged to a depth of around two diameters to reduce wave-making drag and response to waves. Their tail cones should have a length-diameter ratio of at least two to minimize drag. Tests show that a simple hemispheric nose provides about the same net drag as a more streamlined elliptically-shaped nose (reference [2], Part II). Four struts are used instead of two for several reasons: (*a*) they provide a greater metacentric height in both pitch and roll with less waterplane area, (*b*) they produce much less wave drag at the selected design speeds since they are operating at super-critical wave-drag Froude numbers, (*c*) they have less frictional drag for the same hull submergence, (*d*) they are less costly to fabricate since they are smaller and have simpler forms; they do not require complex shapes to reduce wave drag, (*e*) they permit operation in higher sea states since the hulls tend to be more deeply submerged when comparing optimum designs, (*f*) they provide less motion in waves since their waterplane area is smaller, (*g*) they provide better burst speed capability since the added wave-making resistance at speeds above design speed tends to be smaller, (*h*) they provide better maneuverability with less sideslip and drag due to their greater keel depth, greater aspect ratio, and the fact that a gap exists between the struts, (*i*) they permit full control over yaw and sway in waves by incorporating rudders in each strut, and (*j*) they have less sideward virtual mass so they will respond less to beam seas.

The design and development of an S^3 requires a different approach than conventional ships. Portions of the design would center around torpedo and hydrofoil boat technology. Other portions would draw upon aircraft, ship, and submarine technology. The hydrodynamic aspects relate to the flow around torpedo-like bodies and hydrofoil struts and control surfaces. The structural design would require aircraft techniques for the upper platform and the struts, and torpedo techniques for the hulls. The power plant design would generally be based upon aircraft gas turbine technology. The determination of seaworthiness and control forces would require model tests and the application of hydrodynamic theory based upon submarine, torpedo, ship, and hydrofoil technology. The electronics, control, and sonar design would be based upon torpedo, ship, and hydrofoil boat technology.

Fig. 2 contains drawings of various sizes of S^3 ships showing how the general form may change with size. Also presented in Fig. 2 are typical values for the basic dimensions and estimated speeds for arbitrarily selected shaft powers.

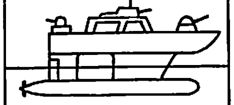
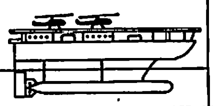
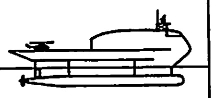
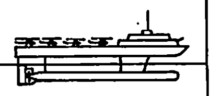
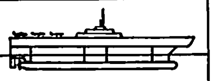
SHIP FORM	WEIGHT (L. Tons)	MAX. SPEED (Knots)	TOTAL POWER (HP)	LENGTH and BEAM (Ft)	CYL DIA. (Ft)	HULL to CYL. DIST. (Ft)
	100	43	10,000	66x33	5.5	14
	500	43	30,000	113x56	9.4	18
	2,000	40	60,000	180x90	15	20
	10,000	36	120,000	350x150	25	25
	80,000	35	400,000	1200 x 300	35	30

Fig. 2 Typical characteristics of various S^3 sizes

The design form of an S^3 design will change not only with size but also with speed and mission. As the ship size increases, the nondimensional water clearance and the ship height/length ratio will decrease; the dimensional water clearance, however, will still tend to increase with ship size. This form change reduces the distance between the center of buoyancy and center of gravity, which in turn provides the required metacentric height with reduced nondimensional strut sizes and sideward spacing. Therefore, the larger S^3 designs will tend to become more elongated with size. Increased speed requires larger power plants, and also more fuel. This may result in larger submerged hulls and a smaller spanning platform. Wider ships may be required for V/STOL aircraft platforms. Designs with large, heavy, sonar suites or with unusually large payloads in the hulls may have lowered centers of gravity which would tend to reduce strut size and spacing in order not to exceed the desired metacentric height.

In regard to the draft, it is apparent that the larger S^3 designs must reduce their draft in harbors. One means of designing a reduced draft, and yet maintaining a centerline hull depth of around 1.8 to 2.0 dia, is to utilize a flattened elliptical hull cross section rather than a circular cross section. For example, the draft of a 3,000 ton S^3 would be only 31 ft if each hull was 13 ft deep and 20 ft wide. A 13-ft circular hull could be the pressure-resistant structural core and the elliptical extensions could be pressure equalized at ambient and contain the fuel. If provision was made for topping off the fuel tanks in deeper water, the draft would be only 13 ft when fully loaded, except for about 70 to 80 percent of the fuel. Even larger S^3 designs could enter the deep-water harbors without requiring a ballast change.

If a change in draft is needed for harbor operation, one of the more efficient methods is to top off the fuel tanks, as mentioned above. An alternative method would be to design expansion chambers into the hulls or struts. Another approach, but more costly and complex, is to retract the struts. A less efficient means is to carry water ballast. Still another approach is to design the struts with a large flair at their upper ends so that, when loaded at rest, part of the flair is under water to reduce the draft. When underway, the S^3 could be raised dynamically to reduce its drag; the fuel used en route need not be entirely replaced by water ballast as in the normal S^3 case so its draft at rest would be even less at the end of a trip.

For the situation where large loads are suddenly added or taken away while underway, the automatic control system could compensate to provide a near-level flight and constant draft. In the static situation, the changes in draft are generally not serious, as one might think, even though the waterplane area is quite small. For example, on a 5000-ton ship, its draft change would only be about 5 ft with a payload change of 250 tons, which represents twenty-five 10-ton helicopters or 3000 men.

Many variations in design form are possible from the four-strut, twin-hulled S^3 design version discussed in this report. For example, one submerged hull and three or more widely-spaced struts may be utilized. Alternatively the ship may rest on the upper platform at zero speed and rise, using hydrofoil lift, as the speed increases. Another approach is to let the hulls be slightly exposed at rest, and drive them downward when underway.

Some new uses for the S^3 may result by joining several of them together to form a large, stable ocean platform. The platform could be desinged so each of its S^3 modules could operate independently to disperse the platform. Two of the S^3 modules could be high-powered supply ships which travel back and forth at high speed to a home port and which, when coupled to the remaining part of the platform, could propel it at moderate speed.

Although the basic soundness of the S^3 concept has been demonstrated, the large number of design parameters (e.g., hull separation, strut position, strut waterplane area, submerged hull depth, control and stabilizing fin sizes, number and placement) allow optimization for special applications.

Efficiency. One measure of ship efficiency is its speed for a given weight and power output. The nondimensional form of performance is WV/P

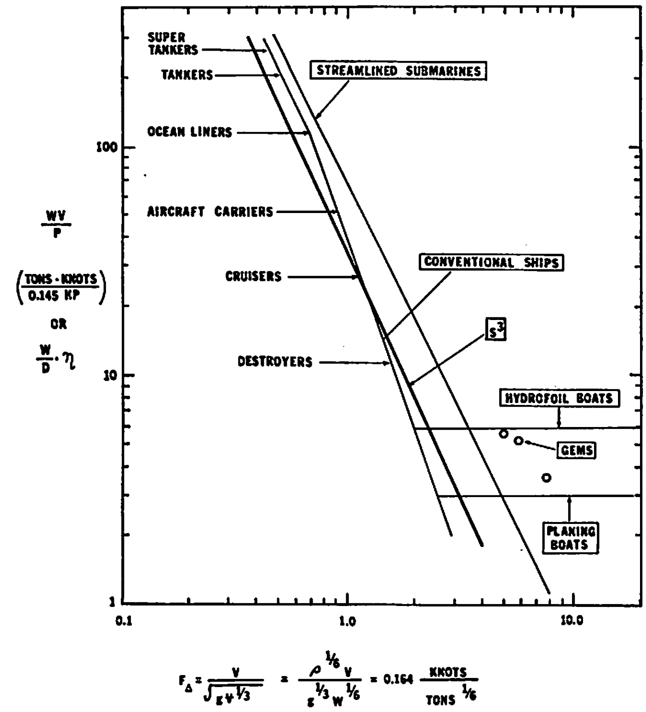


Fig. 3 Efficiency of various ship types

where

W = total ship weight,
V = top speed, and
P = maximum power output.

This same performance criterion is valid for comparison with hydrofoil boats, ground effect machines (GEMS), aircraft, and many other types of vehicles. When graphed against the design parameter F_Δ, the nondimensional performance of a wide variety of types and sizes of vehicles can be compared. Large numbers of data points collapse into a few simple bands on the graph giving an overall view of the operating regions where each of the vehicles are most suited. The basic design parameter is the displacement Froude number

$$F_\Delta = V/\sqrt{gl'} = V_\rho{}^{1/6}/g^{1/2}W^{1/6}$$

where

$l' = \forall^{1/3}$,
$\forall$ = ship displacement = W/ρ_g
ρ = mass density of water, and
g = acceleration of gravity.

Although other nondimensional design parameters are also important in determining vehicle design form (reference [12]), F_Δ is the most significant. Fig. 3 is a plot of approximate values of WV/P versus F_Δ. It shows that the S^3 is more efficient than conventional high-speed ships, less efficient than tankers, and more efficient than hydrofoil boats or ground effect machines below a value of F_Δ around 2.2 where F_Δ = 0.164 kn/tons$^{1/6}$. For example, F_Δ for a 3000-ton S^3 operating at 40 kn would be 1.73; the efficiency of the S^3 would be about double that of a hydrofoil boat according to Fig. 3.

The drag of an S^3 at design speed is

$$D = C_d(\forall)^{2/3}\frac{\rho}{2}V^2$$

where C_d = drag coefficient = 0.04 to 0.05 for ships of several thousand tons. The drag can be estimated using the methods of reference [14] with the exception of strut spray drag. Strut spray can be reduced by a factor of three using horizontal spray rails located above the water line and configured according to reference [15]. Reference [15] shows that strut spray drag, with spray rails, is approximately equal to the frictional drag of a strut having an additional wetted surface area of about 0.2 c^2 where c is the chord length. Ejection of polymers at the hull and strut noses could reduce C_d somewhat for periods of several hours and provide burst speed capability.

The required shaft power P is

$$P = \frac{D\cdot V}{\eta} = \frac{C_d}{\eta}(\forall)^{2/3}\frac{\rho}{2}V_3$$

where η = propulsive efficiency = 0.80 for well-designed S^3 at low to moderate speeds. This efficiency is higher than that of conventional ships because the propellers operate under more uniform and somewhat more symmetric inflow conditions. Also, it is assumed that the propulsor is designed to recover some of the hull boundary layer energy.

The efficiency of submarines is seen by Fig. 3 to be relatively high. In general, the value of C_d for a smooth, well-designed torpedolike vehicle or towed submerged pod is around 0.022 (reference [13]). The addition of a conning tower or other protuberances would increase this value to around 0.025 or more.

Static Stability and Natural Periods. ¡The S^3 is statically stable if its metacentric height GM is posit ve. The value of GM determines the degree of static stability and for roll is:

$$GM = \frac{I}{\forall} - BG \doteq \frac{Ab^2}{4\forall} - BG$$

where

I = moment of inertia of the waterplane area about its longitudinal centerline,
A = net waterplane area,
b = centerline strut spacing,
$\forall$ = displaced volume of the ship, and
BG = distance from the center of buoyancy to the center of gravity.

Model tests and analysis of roll due to wind and waves indicate that GM should lie between 0.50 and 0.75 hull dia (reference [2], Part II). Tests show that even larger values would slightly reduce motion in waves, contrary to conventional ship results, but the drag or structural weight would increase due to the larger struts or increased spacing required. The GM in pitch is calculated similarly, using the longitudinal strut spacing.

According to simplified analysis, the natural periods in pitch, roll, and heave (reference [2], Part II) are approximately:

$$(T)_{\text{pitch}} \doteq \frac{2.67l}{\sqrt{g\cdot GM_{\text{pitch}}}}$$

$$(T)_{\text{roll}} \doteq \frac{4.87b}{\sqrt{g\cdot GM_{\text{roll}}}}$$

$$(T)_{\text{heave}} \doteq 10.9\sqrt{\frac{W/\rho g^2}{\Sigma\left(\frac{t}{c}\cdot c^2\right)}}$$

where

l = ship length,
W = total weight,
$\frac{t}{c}$ = thickness-to-chord ratios of the struts,
c = strut chord length, and
g = acceleration of gravity.

In practice, the pitch and heave modes tend to be highly coupled. Also, considerable damping exists which changes the frequency somewhat from the above idealized values. The dynamic natural frequencies are not important since test results show that well-designed versions of S^3 ships are nearly critically damped in pitch, heave, and roll.

The roll angle due to wind (reference [2], Part II) is approximately

$$\Theta = \sin^{-1}\left(0.00176\,\frac{U_w^2}{g\cdot GM_{\text{roll}}}\right)$$

where U_w = wind speed.

Hydrodynamic Coefficients. The hydrodynamic coefficients in pitch can be approximated at higher Froude numbers (reference [2], Part II) using aerodynamic theory, since the hulls and horizontal surfaces are well submerged. The presence of the free surface, however, distorts the flow at lower Froude numbers; so the calculations must be somewhat modified.

The coefficients in yaw can be similarly approximated at higher Froude numbers using aerodynamic theory by assuming that the free surface makes the struts behave as if they were cut off at that point and fully submerged. As one would expect, considerable downwash effects occur on the aft struts. At lower Froude numbers, test results (reference [2], Part II) show that the coefficients in yaw are markedly changed.

Model Test Results

A series of about 500 exploratory test runs were made on various 5-ft models in the General Dynamics Aeromarine Test Facility model towing basin in San Diego, California, during August and September 1969. The towing basin is 315-ft long, 12-ft wide, and 6-ft deep. Additional tow tests were made in March 1970 in San Diego Harbor when one of the models was towed by a line to obtain additional data on drag and dynamic response. On the basis of the various test results, a 5-ft self-propelled radio-controlled model (Fig. 4) was designed and fabricated. Testing began in September 1970. In March and May of 1971, additional tests were conducted on a self-propelled 11-foot model at NSRDC.

Five-Foot Towed Models. The following kinds of tests were conducted and reported in Reference [2], Part II:

1 With the models fully restrained, towing tests were made at speeds of 2 to 15 fps at five different drafts in smooth water and in 2-in. to 6-in. head and following waves using various model configurations. All model hull diameters were 4 in. The model lengths, widths, and appendages were varied. Drag, side and lift forces, and pitching and yawing moments were measured. The angle of attacks in pitch and yaw were also varied.

2 Semirestrained tests with the models free to pitch and heave were made at towing speeds of 2 to 15 fps for the purpose of measuring the stability and response of various model configurations in smooth water and in head and following waves.

3 Station-keeping tests (models at rest, but free to roll, pitch, and heave) were made with the models at headings of 0, 45, 90, 135, and 180 deg to waves of selected heights and lengths for the purpose of measuring motions. The metacentric heights were varied during these tests and the natural periods of roll, pitch, and heave motion were recorded.

Also, limited tests were made of a model free to drift in waves and of a partially-restrained model in calm water in winds up to 20 mph to determine wind drag forces and model drift angles.

For comparison, the model of a more conventional displacement ship (C-4 type hull) was towed in waves at speeds of 4 to 12 fps with heave and pitch motions measured by instrumentation. The model motions were also recorded on 16mm color film, and additional motion pictures of the C-4 ship model were made while it was alongside the semisubmerged ship, both being completely free in waves.

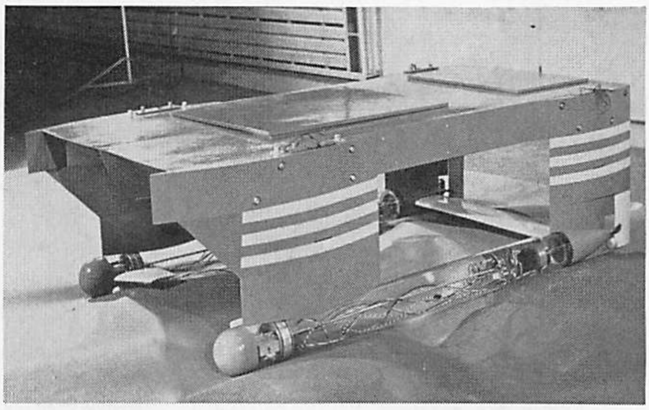


Fig. 4 Photograph of the 5-ft radio-controlled model

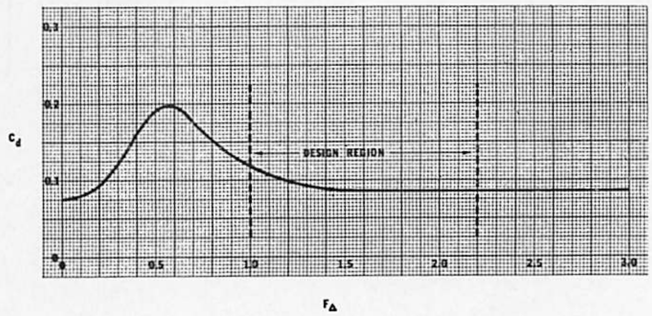


Fig. 5 Drag coefficient of a towed S^3 model

The average of the tested model drag coefficients, based on $\forall^{2/3}$, is shown in Fig. 5 graphed againt F_Δ. The design region for ships displacing a few hundred to several thousand tons is $1.0 < F_\Delta < 2.2$. In this region, wave drag is small to negligible. After correcting the model data to the Reynolds numbers of ships and reducing the spray drag to account for inclusion of spray rails, the value of C_d at F_Δ = 1.5 to 2.2 would be around 0.04 to 0.05. Most of the hump drag around $F_\Delta = 0.55$ is due to strut wave drag. The front struts had a $\frac{t}{c}$ ratio of 16 percent, and the aft struts 12 percent. The front and aft struts had chord lengths of 3.75 and 2.5 hull dia, respectively. There were no canard fins on this first set of models. The drag tests showed that reduced draft reduced drag at all speeds, that waves had no significant effect on average drag, and that angles of attack in pitch and yaw of 3 to 4 deg had little effect on drag.

The motion results showed that the S^3 is stable in all respects, all natural frequencies are well damped, and motion in waves is small relative to conventional ships. The results indicate that small canard control surfaces and flaps could provide a level ride in either direction in waves whose height was significantly larger than the hull diameter.

Five-Foot Radio-Controlled Model. This model is 56.82-in. long, displaces 61.51 lb in fresh water, and has the same hull dia, water clearance, platform thickness, and draft as the towed models described above. The front struts, however, are placed much nearer to the hull noses, and their leading edges are swept forward in the region of the water line. The metacentric height in roll is 3.0 in. with the center of gravity 1.3 in. above the water surface. Small canards, utilizing the analysis of reference [2], Part III, were designed and placed near the hull noses for pitch and roll control. Trim tabs were placed on the aft stabilizer, and twin rudders 6-in. high with a 2.7-in. chord length were incorporated into the aft struts behind the propellers. The model is propelled by two electric motors, one in each hull. The motors are rated at around 0.15 to 0.20 hp.

The test results showed that the model was stable in all modes and well controlled. The model will pivot at rest around its vertical centerline with one propeller thrusting forward and the other thrusting aft. Also, it can accelerate forward or reverse at maximum power. When moving, the canards provide strong control over pitch, heave, and roll, even at relatively low speeds. At rest, the model is highly damped in heave and pitch and moderately damped in roll. When running, it is highly damped in all modes. Tests in the seakeeping tank at Offshore Technology, Inc., at Escondido, California, showed that response was acceptable at all angles to waves, and that a following sea tended to produce the greatest motion and head seas the least motion.

Wind tests indicated that the model turns slowly broadside, and that it can withstand a wind of 25 mph before the platform begins to touch the wind-generated waves in the tank. Wind speed scales by the square root of length; so a 3000-ton S^3 can withstand 175 mph winds. The wind-induced roll angle tends to agree with theory presented earlier.

When tested in San Diego Bay, the model safely traveled through any ship-generated wave without significant impact on the cross structure. The model has a natural tendency to bank in turns without canard control. Also, sufficient canard control in roll exists so the model can be banked more in turns, or can negotiate flat turns, if desired. With only one motor on, the model was easily controlled and ran straight with no observable yaw angle and a rudder deflection of only about 6 deg.

Eleven-Foot Model Tests. The 11-ft self-propelled model was tested at NSRDC to provide hydrodynamic data on a 190-ton version of an S^3 designed by NUC. The data reduction is still in process at the time of this writing. Qualitative results show that the drag and response to waves are essentially identical to those of the 5-ft radio-controlled model.

Summary

A considerable number of model tests, design studies, and mission analyses have been conducted on the S^3 design concept. The results show that the S^3 is highly stable and seaworthy (both at rest and underway), more efficient at design speeds than conventional ships, and appears to be superior to other ship types for many kinds of naval missions and nonmilitary applications. The S^3 is most attractive in the size range of 100 to 15,000 tons, at speeds from 25 to 45 kn, and for applications which require reduced motion in waves. The concept is so promising that a 190-ton experimental model is being designed to further explore the S^3 concept and to serve as a work platform for supporting oceanic research projects.

Acknowledgments

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DISCUSSION

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The history of naval architecture is rich in invention and innovation, but a disappointingly small proportion of the many suggestions for improved efficiency or safety of marine transport have eventually established themselves on the maritime scene. It seems that significant change comes only when the nature of the required function of the marine vehicle changes (perhaps to accommodate a new cargo, a new route, a new type of cargo transfer or weapon system) or where some new technology becomes available (e.g., in materials, prime movers, energy conversion systems, or production methods) which either effects major improvements in existing systems or enables an old (previously unsuccessful) idea to be successfully resurrected and made viable.

The concept presented in this most interesting paper perhaps fits most nearly into this last category—an earlier idea re-developed with the sophistication of contemporary technology. The S^3 is proposed not for a radically new function nor in response to development of new weaponry or cargo transfer systems, but rather as a new maid-of-all-work, suitable for a variety of roles (including cargo ships) in a range of sizes from 100 to 15,000 tons. Such potential cannot fail to excite the interest of the naval architect and shipowner alike, for whom the many advantages cited for the S^3 in the Introduction must have great attractions.

The concept clearly offers a greater degree of flexibility in designing hydrodynamic and motion characteristics than is available for more conventional craft; and for maritime functions in which more precise motion control and large deck area are needed, then the S^3 design seems likely to be competitive, provided robust and reliable control systems can be developed. But in respect of other characteristics, and particularly in relation to the all-important question of transport efficiency, the evidence presented in the paper is too slender on which to base any firm judgment.

Take the question of drag, for example. Certainly the submerged hulls, suitably designed, will enable wave-making resistance to be reduced compared with conventional hulls of the same displacement. But the other drag components, augmented by

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the various appendages and control surfaces, may well be significantly increased. In the Froude number range of most commodity carriers, the resistance characteristics of the S^3 (as evidenced by Fig. 5) seem to compare unfavorably with conventional vessels. For such transport functions the S^3 only begins to look attractive if there is a requirement for a fleet of small fast craft. But this is contrary to the present trend for merchant ships, where the economies of scale (with rather small variations in speed) have now been well established as leading to greater transport efficiency.

And even at higher Froude numbers the improved efficiency of S^3 is not convincingly demonstrated by Fig. 3. For efficiency, as there defined, is not the proper criterion on which to base a choice of design concept. Fig. 3 indicates a kind of hydrodynamic efficiency in relation to the power needed to achieve a certain total momentum. But to many operators it is the momentum of the *payload* that matters. This emphasizes the importance of the payload/displacement ratio, on which the information in the paper is rather sparse and not very encouraging. For merchant ships, this ratio is of the order of 0.7 to 0.9, and even for hydrofoil and hovercraft ratios of 0.4–0.5 are achievable in the present state of the art. The high structure weight of S^3 is clearly one of its major technical drawbacks, and it seems that the future viability of this type of craft depends to a large extent on finding ways of reducing this component of weight.

The structural problems are severe, but probably not insuperable. When the writer was involved in the design of a SEMCAT (a large semisubmerged catamaran) nearly ten years ago, it was found that the design of the structure to resist transverse loads, such as would develop particularly in a beam sea, was a critical feature of the design. High transverse bending moments can occur where the vertical struts meet the superstructure unless some lateral bracing is provided. Is the after horizontal fin intended to fulfill this structural function also? Recent tests on a model catamaran fitted with such a fin showed that high pressures can develop on it due to ship motions. It must therefore be designed as a "beam-column" to withstand loads both normal to and along the axis of the fin, and will thus be a significant item in the structure weight.

The author recommends aircraft technology as an aid to structural design. Recent advances in stress analysis and design of marine structures could just as well be used, and might avoid the tendency of aircraft technology to escalate the initial costs of the structure. On this aspect also, the further studies of the N.U.R.-D.C. team will be awaited with interest. The stated reduction in cost through "modular design and geometric simplicity of components" might not apply with equal force to the struts, control surfaces, and control systems, especially if aluminum is used extensively.

Such arguments, and the lack of precise data on which to base comparative studies, point to the conclusion that S^3, although an interesting concept with some attractive features, has yet to be established as a serious competitor in most of the roles suggested in the paper. Like many engineering innovations, its particular advantages are likely to be more than offset by other disadvantages, so that a detailed life-cycle cost study of the craft, in various sizes and roles, will probably indicate, as with hydrofoils and hovercraft, that it is a potential competitor only for a rather narrow range of functions. The original role envisaged for it may well prove to be the right, if not the only, one. But even though the writer does not altogether share the author's optimistic view of the wider potential of S^3, it is very much to be hoped that research on the concept will continue at high priority, so that the basic problems can be identified and solved, and quantitative data published on the important technical and economic aspects, so that its relative merits vis-à-vis other craft can more clearly be judged.

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