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Low-Water Plane Multihull Ship Principles, Status, and Plans for Naval Development

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Nomenclature

B_X = beam at midship section
T = draft
EHP = effective horsepower
R_f = frictional resistance
V = forward velocity
GM = metacentric height
C_X = midship section coefficient
C_P = prismatic coefficient
$P.C.$ = propulsion coefficient
R_r = residual resistance
Re = Reynold's number
SHP = shaft horsepower
R_t = total resistance
w_t = wake fraction
L = waterline length
R_w = wave resistance
h = wave height
S = wetted surface (also $W.S.$)
Δ = displacement volume ($V = 35\Delta$)
∇ = displacement weight
ω = frequency term
η_H = hull efficiency
ν = kinematic viscosity of water
η_O = propeller efficiency in open water
η_D = propulsion coefficient (delivered)
η_R = relative rotative efficiency
ζ_A = wave amplitude
λ = wave length

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I. Introduction

Overview

"IN short, I firmly believe that the best way to get better ships for less investment is through better concepts and designs. If we do not go this route, we will not get the ships." Hon. John Foster in 1971 speech to ASNE.

The Navy has been investigating concepts for seagoing platforms with performance capabilities to meet future special requirements. These special requirements grow out of progressively increasing volume requirements of the weapon systems employed coupled with their increasing demands for platform stability in a seaway. Most Navy surface ships are now volume-limited, excluding tankers and some other special ship types.

In its search for major improvements in performance, the Navy has investigated hydrofoils, air cushion vehicles (ACV), surface effect ships (SES) and the conventional catamaran. Each has development problems and limitations in size, speed, and mission. This paper describes the principles and potentials of the Low-Water Plane (LWP) multihull ship. In the last four years this type of ship has received widespread attention throughout the U. S. and abroad. It has three distinct parts: underwater hull, abovewater hull, and connecting struts. Two of many possible configurations are shown in Figs. 1 and 2. The underwater portion is a buoyant member which supports the abovewater portion, in the form of a deck platform, on one or more streamlined, connecting struts per side which also supply a fraction of the total buoyancy.

This paper will not delve into mission analyses or scenario developments in response to existing or postulated threats facing the U. S. Navy. However, it is worthwhile to expose our thinking in this area. To prove the value of the LWP multihull concept, the planned development program ought to evaluate: a) the operational advantages of a LWP multihull ship which carries payload items identical to those on conventional warships; b) the unique features in the LWP multihull ship which might make it advantageous to redistribute the mission equipments of a task force among its monohulls and LWP multihulls (possibly among its hydrofoils and SES also); c) whether it might be easier to adapt some future weapon systems to the LWP multihull concept than to conventional monohulls, e.g., AN/SQQ-23 PAIR sonar, one transducer mounted underwater on each LWP bow as opposed to one behind the other as now forced by conventional monohull features, or the use of a conformal planar array sonar; d) the feasibility of incorporating modular design concepts into LWP multihull ships for ease of reconfiguration and to facilitate repair or replacement of systems. If any one of these advantages is attractive, then there is merit in proceeding with the proposed development program. If all are correct, then it may be the breakthrough we have been waiting for since the first steel ship was built or the propeller replaced the paddle wheel.

The LWP concept is derived by optimizing a hull form utilizing basic hydrodynamic principles governing bodies operating at a free surface. Proper application of these principles reduces hull resistance resulting from: a) wave energy imparted to calm water by a body passing through it, b) travel through rough water, and c) motions induced by the seaway on a body traveling at a free surface.

The resulting hull form minimizes the adverse effects of operation at the interface of two largely different media. The result is a vessel of high lift/drag ratio (low resistance per ton of displacement) for specific speed and payload density regimes, with substantially reduced motions. Additional advantages compared to other competitive hull forms are: a) Good seaworthiness qualities (stable platform not at expense of powering). b) Highly arrangeable space (box-like stowage volume from stem to stern) in prime location high in the ship. Adaptability of this box-like structure further lends itself to use of modules or containers for fast and economical changes of payload. c) Low-production cost (mostly flat plates and simple repetitive shapes). d) High degree of survivability (upper hull not hit by underwater explosion can serve as second hull when lower hulls are damaged).

On the other hand, only specific ship types can take advantages of the LWP hull form; i.e., ships which carry low-density payload and require large top-side space such as Sea Control Ships, destroyers, and some auxiliary ships (but not tankers or bulk carriers). There are also some disadvantages to the very features which make it attractive in the first place; i.e., low-water plane area and multihull.

For example, an inherent characteristic of the low-water plane area is a reduced hydrostatic restoring force in response to an imposed load. To substitute for the natural counteractive buoyancy inherent in normal ship forms, this LWP characteristic requires that artificial means be introduced, such as automatic ballasting and deballasting at zero and low speeds, or some other physical changes when the platform is at standstill, and dynamic lift compensation at higher speeds from underwater control surfaces.

The LWP multihull feature also introduces three basic constraints: high-directional stability which resists maneuvering of the vessel; a broad beam in larger versions, which will exceed capacities of current drydocks and the width of the Panama Canal; and a deep draft which will limit the harbors and channels to which it will have access. Thus, some operational limits may have to be accepted to achieve the benefits of the concept. In any case, they are all subject to tradeoff studies on a case basis. Additional problems in structural design and delivery of pro-

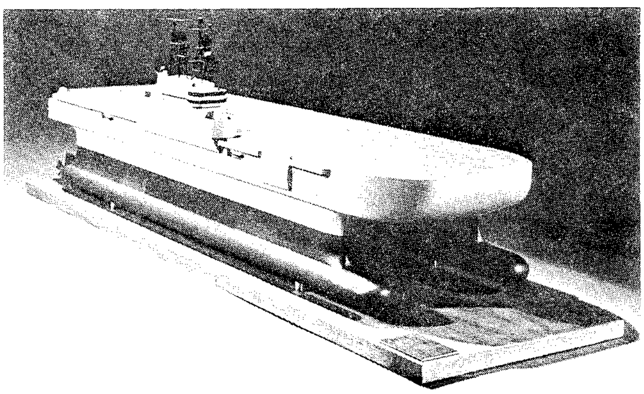

Fig. 1 Display model of TRISEC-concept applied to LHA.

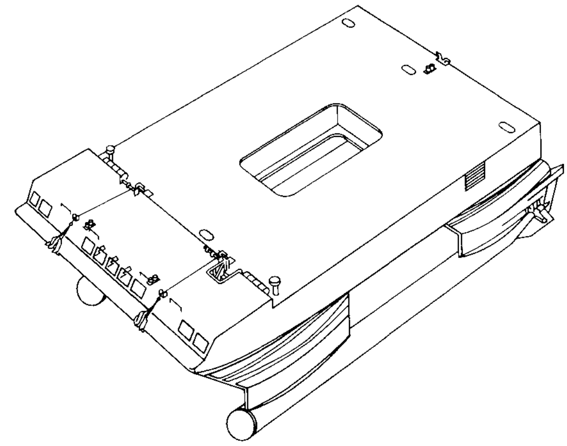

Fig. 2 The SSP (Semi-Submerged Platform) designed by NUC.

pulsion thrust are solvable without extending the state-of-the-art (within certain ship size limits). Recognition of these problems and need to demonstrate their solutions in a sufficiently large vessel are discussed in Plan for Development.

II. History

A single-hulled LWP ship was invented in 1880 by Lundborg.[1] The first multihulled design appears to have been invented by Blair in 1930.[2] Another surfacing of the twin-hulled version occurred in 1946.[3] In 1959 Boericke,[4] in the Navy's Bureau of Ships, proposed the shark form which is an improved, modern version of Lundborg's approach. Boericke did this at about the same time Mandel and Frankel[5] investigated exhaustively the behavior of the single-hull LWP. The mohole platform was proposed in the 60's as a mobile drilling rig[6] and is similar to the Blair design. In 1965 Frankel,[7] at MIT, proposed another version of the mohole platform, called SEMCAT, for the purpose of open ocean retrieval of large objects. In 1968, an MIT student proposed yet another version of the multihull design.[8] In 1969, the Netherlands Offshore Company launched a 1200-ton twin-hulled drilling rig called *Duplus.*[9]

In March 1967, during Phase A of the LHA competition, Litton Industries presented a ship concept, Fig. 1, obviously too experimental in nature to be seriously considered for the ongoing LHA acquisition program. Several distinctive features were introduced by Litton's TRISEC: noncylindrical cross section of the lower portion of the hulls, partial dynamic lift obtained by the lower hulls or large foils attached to the lower hulls, variable depth of operation as a function of ship's speed and single large struts (one per each lower hull).[10,11] These features, along with the derivation of the basic principles which make the concept feasible, laid the ground for future refinement and exploration. A patent was issued to Leopold and assigned to Litton Industries on June 3, 1969.[12] At first glance, the physical appearance of the various designs and their names, such as Semi-Submerged Platform (SSP), Semi-Submerged Ship (S^3), Modified Catamaran (MODCAT), and Sea-Sulky seem different, but they all strive to take advantage of the same principles and features presented in Refs. 10 and 12 and Fig. 1.

In 1969, work on the LPW multihull ship concept was initiated at two Navy laboratories. Naval Undersea Center (NUC) on the West Coast settled quickly on a two strut per hull configuration. On the other hand, Naval Ship Research and Development Center (NSRDC) on the East Coast began building a general foundation from which to develop LWP multihull analyses, as a rational extention of their already established commitment to the catamaran concept.

During 1970 and 1971, NUC, NSRDC, and Litton vigorously pursued LWP model testing and paper analyses. NUC designed a 200-ton, 80-ft LWP vessel, called the SSP, under the leadership of Lang. The SSP design was tested at NSRDC using both towed and self-propelled models, Fig. 2. In July 1971, NAVSEC conducted a safety study of the SSP design. With some minor changes, NAVSEC approved the SSP design as safe, and NAVSHIPS approved it for production at the Pearl Harbor Naval Shipyard. The model test results of the NUC design called S^3 were summarized by Lang[13] in Nov. 1971.

Continuing its in-house commitment to the catamaran concept, NSRDC conducted conceptual studies and made model tests of LWP multihull configurations for both small and large aircraft carriers.[14] Work was also initiated on developing procedures for devising a LWP multihull with low-wave drag based upon fundamental research conducted on conventional catamarans.[15] Similar endeavors were also undertaken for determining the added mass and damping of arbitrary catamaran section shapes for use in catamaran motion and sea load predictions.[16] Model tests were conducted on a 15-ft model of the smaller carrier, designated MODCAT I; on a 20-ft model of the large ship, MODCAT II; and on an 11-ft model of the NUC design, S^3. Resistance, propulsion, and seakeeping tests were performed on all three models. Concurrently with these hydrodynamic studies, NSRDC conducted extensive structural analyses and small scale experiments on various other designs.

In early 1971, NSRDC mounted a major in-house program to develop a 4300-ton, 33-knot, high-performance LWP multihull concept. Possible missions were examined. The first configuration developed and model tested was MODCAT III.

Litton also continued investigations and accumulated pertinent data through model tests. In 1970, model tests were performed at the Netherland Ship Model Basin where various underwater hull diameters and strut thicknesses were tested on single-LWP hulls leading to a wealth of parametric data. In addition, in 1971, Litton built a 25-ft self-propelled model of TRISEC and tested it on Morris Dam Lake, Calif. The model was large enough to be operated by two people.

III. Description of the Concept and Derivation of Its Principles

Background

The surface ship operates in a unique environment. Unlike submarines and aircraft, it travels at the intersection of two largely different media—air and water. Two basic performance characteristics for conventional surface ships, i.e., resistance and motion, are seriously degraded by this intersection. In order to avoid this degradation, especially that due to rough water, departures from the conventional hull form, such as catamarans, trimarans, and twin-hull designs, have resulted. Similarly, vehicles which depart in both directions away from this free surface, i.e., submarines, semisubmarines, hydrofoil boats, and surface effect ships, have been conceived.

The problem with conventional displacement ships stems mainly from the fact that an efficient shape from the standpoint of stowage adversely affects its hydrodynamic characteristics, namely, through high resistance and severe motion. Problems related to powering are principally due to wave-making. Wave-making resistance is the reason a large ocean liner designed for 40 knots would pay a penalty as high as a 40% increase in power for each additional knot of speed.

Problems relating to motion arise from high responsiveness to a broad spectrum of wave induced frequencies in almost all six degrees of freedom.

The extraordinary features of the LWP multihull ship are its small waterplane area and large hull separation. The unusually small waterplane area is made possible by connecting the large submerged hull(s) to the deck platform by a pair of thin struts, insuring stability by adequate hull separation. This is exactly the reason which makes the LWP multihull ship more attractive than a conventional catamaran.

On an equivalent displacement basis, a conventional catamaran may have two hulls of finer beam/length ratio as compared to the conventional ship, to reduce a certain amount of wave-making resistance. However, due to the appreciable increase in wetted surface plus the wave interference effect of its two hulls, a catamaran generally has higher resistance than a conventional hull. Although the LWP multihull ship suffers the same drawback of large wetted surface, it has low wave-making resistance at high speeds due to its distinctive geometrical feature, the very small waterplane area. It also shows little wave interference effect because of its low wave-making struts and large hull separation.

A system which lends itself to better over-all optimization is the one where the cross-coupling terms are the weakest, since then each individual quality can be optimized independently with respect to its own variables without degrading others. This is the case for the LWP multihull ship compared to a conventional hull. For example: seaworthiness is decoupled from seakeeping characteristics, and efficient stowage for payload utilization is decoupled from efficient hydrodynamic shape.

In addition to improved performance at high speeds, LWP multihull ships possess features which could allow flexibility in fleet operations. The vessel could be designed to get underway with minimum draft (and consequently, minimum wetted area and frictional resistance), then to settle as a function of speed to offset the wave-making resistance. This is accomplished through an effective change in the shape that is presented to the flow without a physical change of shape.

Another characteristic of catamaran ships, and the LWP multihulls in particular, is that they are weight-limited because they have more volume than one can fill. This can be seen from the following argument: ignoring certain small hydrodynamic effects, if the separation of the hulls is increased, the enclosed volume and weight of the cross-structure is increased; and so, to maintain the same draft, the payload weight must be decreased. Therefore, at some large hull separation, weight of the cross-structure will be so great that no payload weight could be accommodated, even though a tremendous volume would be present.

Let us now turn to a derivation of the LPW principles as related to resistance and seakeeping. In the list of advantages of the LWP concept, these two areas are amenable to analytic treatment. The structural analysis aspect is also amenable to analytic treatment, but it is viewed as an effect part in a cause and effect relationship. Therefore, structure will not be treated in this section on fundamental LWP principles. Rather, structures will be discussed in Sec. IV, Recent Results and Current Work, where major issues which need resolution in the structures area prior to construction of a large LWP multihull ship will be described.

Motions

In the 1950's, research in several places in the world predicted heave forces on various simplified two-dimensional bodies which penetrate the water's surface. In 1962, Newman[17] showed that the amplitude of waves radiated by a body oscillating in the free surface is directly related to the exciting forces acting on the same body in waves. Results further indicated there must be bodies which are free from exciting forces in waves. Using an approximate theory Motora and Koyama[18] predicted the proportions of such bodies and experimentally confirmed that there were bodies which are virtually free from wave-induced heaving forces in waves of specified frequencies. The two-dimensional bodies were of two parts, a lower body cylindrical or elliptical in shape, attached to a rectangular or wall-sided body which penetrated the water surface and which was substantially narrower in beam than the cylindrical body. If this configuration could be incorporated into a catamaran or multihull configuration, it should be possible to reduce motions, and hence, loss of speed in head seas; and, with a lower water plane, decrease roll accelerations without a large increase in roll angle.

Lee et al.[16] recently presented a method for calculating added mass and damping coefficients for any arbitrary catamaran section, including LWP multihull sections, as a function of oscillation frequency. Thus, Lee's work provides the rigorous design tool necessary to develop practical designs.

Resistance and Propulsion

The total resistance R_t of a ship is commonly computed on the basis of Froude's assumption that

$$R_t = R_f + R_r \tag{1}$$

where R_f = frictional resistance, and R_r = residual resistance.

Wave-making resistance R_w dominates the residual resistance term and it is generally agreed that almost all of R_t is due to R_f plus R_w. Despite nearly a century of research, a complete theoretical understanding of the prediction of R_t does not exist.[19] But it is not necessary to address this subject in all its complexity to understand the resistance situation for LWP multihull ships. However, optimization of LWP multihulls will require a complete treatment of the resistance problem in all its complexity.

The theoretical value for R_w is given by Mitchell's integral. In particular, an asymptotic expression[13] for it at high Froude numbers is

$$R_w \cong [(\rho g/\pi L) A_w^2 \log F + 0(F^{-2})] F^{-2} \tag{2}$$

where ρ = fluid density, g = gravitional constant, π = 3.1416 . . . , L = waterline length, A_w = waterplane area, F = Froude number, and O = "Order of . . ."

At higher Froude numbers, the first term in Eq. (2) will dominate R_w, whereas the second term represents higher-order effects due to other geometrical characteristics of the hull. Therefore, an obvious approach towards minimizing wave resistance at high Froude numbers is to minimize waterplane area, either by surface piercing or completely submerged hulls. It is on this basis that the LWP multihull ship was derived.

However, there is more to the story than the implications of Eq. (2). Pien[15] extended the ideas of Ref. 20 and developed a procedure for using theoretical methods to design the underbody-strut combination in such a way as to minimize the waves of the underbodies. This results in lower values of R_w than would result from just minimizing waterplane area. Section IV will expand on Pien's work.

When twin screw propulsion is used to transmit a ship's power, the best achievable propulsive coefficients (P.C.) are about 0.65, where

$$\text{P. C.} = \text{EHP/SHP} \tag{3}$$

where EHP is effective horsepower, which is directly proportional to R_t, and SHP is shaft horsepower, which is power delivered to the propeller. Experience on body of revolution shapes indicates that P.C.'s of about 0.75 should be achievable for LWP multihulls because of potential recovery of boundary-layer energy.

Finally, and most important, the rough water resistance and propulsion situation must be addressed. Unfortunately, quantitative data are not yet available. However, both added resistance due to motions in waves, and loss of P.C. due to oscillations of the propeller and its broaching and operating in an aerated fluid near the free surface, should be considerably reduced due to the smooth ride of the LWP multihull. Conventional monohulls require as much as a 20% increase in power to account for these effects.

IV. Recent Results and Current Work

Introduction

This section surveys recent and current generic research and development work in support of the Low-Water Plane (LWP) multihull concept. It is generally organized by functional problem areas. For example, the Propulsion subsection contains paragraphs on Resistance in Calm Water, Resistance in a Seaway, Machinery, and Propulsor. However, the sum of the contents of this section does not cover all problems one might encounter in the design of an LWP multihull ship. This is because work has been concentrated on problem areas crucial to successful exploitation of the LWP multihull concept. Other problem areas, such as proper location of antennas to minimize electromagnetic interference can be addressed practically only in the context of an actual design.

Propulsion

Resistance in Calm Water

Problems of designing an LWP multihull to have good resistance properties and yet meet other design requirements are more complicated than those of the conventional monohull or catamaran. This arises from a dearth of background experience on this type of hull configuration and from its complex hydromechanics.

The hydrodynamic complexity of the LWP design arises from the fact that the great bulk of the ship's volume will be located near, but below, the free surface. In terms of the submarine designer, it becomes a near-near free surface problem. Superimposed upon the underwater bulk is the vertical strut which, though small, is not negligible in volume. It penetrates the free surface and can, particularly in the resistance component of force, have a strong interaction effect upon the main body. When two LWP bodies are combined into a catamaran, their hydrodynamics are further complicated by both displacement and wave interaction effects between the two hulls. Thus, it is not surprising that the LWP concept has failed to evolve from the frequently successful cut-and-try approach indigenous to much of displacement ship development.

Minimization of resistance throughout the operating speed range of the LWP concept is essential if the configuration is to be competitive with other concepts for accomplishing the same mission. Hence the concentration of much past and present work upon resistance. Residuary resistance R_r is made of hull wave-making resistance, wave interference resistance between the hulls, hull form drag, and eddy resistance created by the hulls or their appendages.

The frictional part R_f is a function of friction coefficient, derived from the Reynold's number. Differences which arise in frictional resistance between monohulls and catamarans stem from differences in Reynold's number and in wetted surface. Differences in Reynold's number between catamarans and monohulls will be small; but, because of the shorter length of the catamarans, the frictional resistance coefficient will be higher. The effect of wetted surface is much more pronounced. Catamarans have much greater wetted surface than monohulls, hence, higher frictional resistance, R_f. Table 1 tabulates characteristics of hulls previously referenced. In Table 1, it may be noted that the wetted surface coefficient $S/(\Delta L)^{1/2}$ ranges from 21.8 to 25.4 for one underbody-strut combination which, of course, must be doubled to account for the two hulls. Typical values for monohulls are 15–16. A LWP catamaran of the same length and displacement would thus have 2.7–3.4 times as much wetted surface as the monohull. Considering the shorter length of the catamaran of the same displacement, the ratio drops down to 1.8–2.4 times as much wetted surface. It is therefore apparent that all means possible should be used in design to further reduce this unfavorable wetted surface ratio concurrently with reducing residuary resistance of LWP multihull configurations to a much lower value than that of competing monohull.

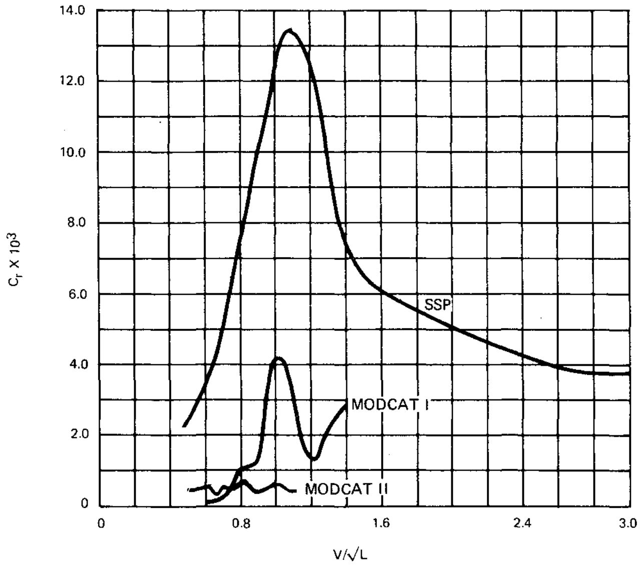

Fig. 3 Residuary resistance of SSP, Modcat I and II.

Table 1 also gives some geometric characteristics of recently designed LWP concepts discussed previously. All have main hulls designed as simple bodies, i.e., simple cylindrical main hulls with elliptic or hemispherical bows, and body-of-revolution sterns of streamlined shape. Vertical struts were either single (MODCAT III and TRISEC) or twin (Mandel[5] and SSP), and of ogival section with uniform vertical area distribution. These designs have essentially treated main body and strut(s) as independent, and have not taken into account in the design stage the strong interaction which occurs between these two components. Efforts have been made to obtain strut shapes which have low-wave drag and main hulls which, from submerged body hydrodynamics studies and experiments, are known to have low resistance.

In Fig. 3, some results of resistance tests on these configurations are presented in the form of residuary resistance coefficient C_R vs speed length ratio $V/(L)^{1/2}$. Since most of these bodies show fine sterns, eddy making is a very small part of C_R. In Fig. 4, the wave drag for a single hull alone is compared to that of one-half the wave drag of the catamaran configuration for MODCAT I. Thus, it is apparent that there are strong interference effects between hulls which are deleterious over most of the speed range. It has also been shown experimentally, as well as analytically, that there are strong wave interference effects between struts and underbodies. These results, along with its large wetted surface, place the LWP concept at a significant disadvantage compared to conventional catamaran or monohull. Thus, it becomes essential to reduce this resistance component to a low value.

Fortunately, while the above explorations were being made, fundamental hydrodynamic research work underway in two areas contributed a solution to this problem. The first contribution was by Pien,[20] who, from the large body of work on wave resistance theory, developed a technique for designing hulls of low-wave resistance. The second contribution,[15] also Pien's, was a technique for determining displacement interference effects between catamaran hulls, then cambering them in such a way that there was no cross-flow hull-induced drag.

In view of the complex hydrodynamics, it is necessary, at this time, to treat the problem in parts; and first deter-

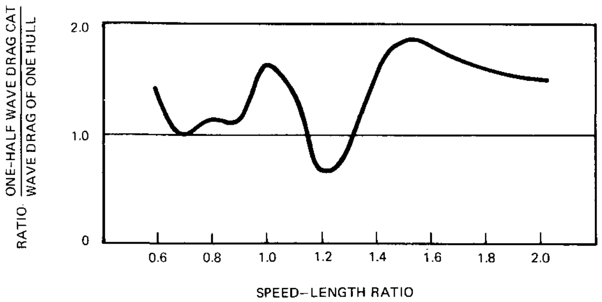

Fig. 4 Comparison of half the wave drag of Modcat I with the wave drag of one side of Modcat I.

mine a single hull configuration with low-wave drag over the speed range. This as previously shown, must include main body and struts, whether one or two, as a total unit. To accomplish this, a computer routine was developed by Pien in which submerged main hull is represented hydrodynamically by a line-source distribution, and strut by a surface-source distribution of appropriate strengths to obtain the desired volume distribution between main body and strut. The program calculates wave resistance. Through a process of compromises between hull geometry and wave drag, a singularity distribution can be obtained for a strut and main body jointly which has low-wave resistance at desired speeds. Once desired hydrodynamic properties have been obtained, it is necessary through another computer routine to trace streamlines in uniform flow to obtain hull geometry which gives desired performance.

Once a good single hull is obtained, it is then necessary to obtain the desired distortion or camber in the hull geometry necessary to minimize resistance caused by presence of the other hulls. Since, as noted above in the previous section, a low-wave-resistance hull has been developed for uniform flow, there is no circulation around the hull. It is desirable to maintain this same flow characteristic when the hull is operating in the presence of another body. To do so means that each hull must be oriented to the curved flowfield created by the other hull so that the original plane of symmetry coincides with the curved flow to maintain stagnation points and avoid creation of circulation. This is difficult because when hulls of large beams are close together, flow on the two sides of each hull are much different. Pien has extended the Douglas program[21] to trace the off-body streamlines for a single hull with a given source distribution. Utilizing techniques outlined in Ref. 15, necessary distortion in hull geometry is obtained to minimize circulation-induced drag. Since the Douglas program assumes zero Froude number, successful application of this approach further assumes a hull of low wavemaking resistance.

This approach has been applied to two configurations. One, a model of a large ship, identified as MODCAT II, has been tested in a towing tank. Its characteristics are found in Table 1 along with SSP—a two strut per side version designed by NUC (see Fig. 2); MODCAT I—a first cut, one strut per side version that did not utilize Pien's approach (it is very similar to Fig. 1); and MODCAT III—a one strut per side model of a 4300 ton feasibility point design that utilized Pien's approach. Figure 5 shows the body plan of MODCAT II along with two comparable

Table 1 Hull characteristics[a]

	SSP Model 5627		MODCAT I Model 5226		MODCAT II Model 5266	MODCAT III Model 5267
Main Body						
L, ft	80.0		520.0		850.0	286.9
B_X, ft	6.5		30.72		70.0	17.34
H, ft	6.5		30.0		38.0	17.34
Δ, tons			9,900.0		39,790.0	1,486.0
W.S., ft^2			45,188.0		117,097.0	12,480.5
L/B_X	10.8		16.9		12.1	16.5
C_P			0.895		0.776	0.758
C_X			0.807		0.794	0.795
$\Delta/(.01L)$			70.4		64.8	62.9
W.S. coef.			19.9		20.1	19.1
Strut	Fwd	Aft				
L, ft	26.5	20.0	440.0		757.5	226.5
B_X	4.0	3.0	17.07		30.4	8.0
C_{WP}			0.83		0.515	0.709
Body + Strut						
H, ft	15.3		60.0	40.0	69.5	32.0
Displ, tons	95.0		16,300.0	11,750.0	50,500.0	2,026.0
W.S., ft^2	2,625.0		67,455.0	53,695.0	164,780.0	19,197.0
B_X/H	0.42		0.51	0.77	1.01	0.54
$\Delta/(.01L)$	185.5		115.9	83.6	82.2	85.5
W.S. coef for 1 hull	30.1		23.2	21.8	25.2	25.2
Propulsion						
Design V, knots	21.0		30.0		30.0	32.0
V/L	2.35		1.316		1.04	1.95
1-w_t	0.842		0.961			
1-t	0.913		0.950			
η_H	1.08		0.989			
η_O	0.66		0.768			
η_R	1.0		1.004			
η_D	0.71		0.763			

[a]For one hull of catamaran configurations.

hull designs: a large catamaran of conventional form and MODCAT I.

Because it is smaller than MODCAT II, MODCAT III has a substantially higher design speed-length ratio and hence, taxes the applicability of Pien's method. Residuary resistance results for MODCAT II, shown in Fig. 3, are an eloquent argument for validity of the approach used, and show that it is possible to significantly reduce wave drag produced by each hull when strut and main body are treated as one entity.

Despite success in reducing its residuary resistance, over-all resistance of MODCAT II is still significantly larger than the total resistance of a conventional catamaran of the same displacement and somewhat greater length, where the latter is designed by methods comparable to those for MODCAT II, or for a conventional monohull of about the same displacement but significantly greater length. Figure 6 compares wetted surface and total resistance in pounds per ton of displacement over the range of speeds of interest to large ships. Since this comparison is made in the lower speed range where wave-making resistance of surface ships is low, these results are not unexpected. In the regime where wave-making resistance is large for the surface ship, it is possible to design the LWP multihull to have low wave-making resistance. Then the smooth water resistance of the two types will be more nearly comparable.

If pending model test results on MODCAT III demonstrate similar success at higher speedlength ratios, then confidence will have been established in this method of design. It then may be possible to reproportion the single hull length, beam, and draft ratios so that there is a significant reduction in wetted surface, and only a small increase in residuary resistance. This brings the LWP multihull into a more competitive position with good monohull designs, and perhaps even improves it over the monohull in the wave resistance speed range. In order that an adequate library of resistance data can be assembled for design and tradeoff studies, it will be necessary to design by this method, and model test a number of hulls with wide variations in speed-length, $\Delta/(0.01L)^3$ and length-draft ratios. When this is done, there will be means available for effective tradeoff studies and design optimizations.

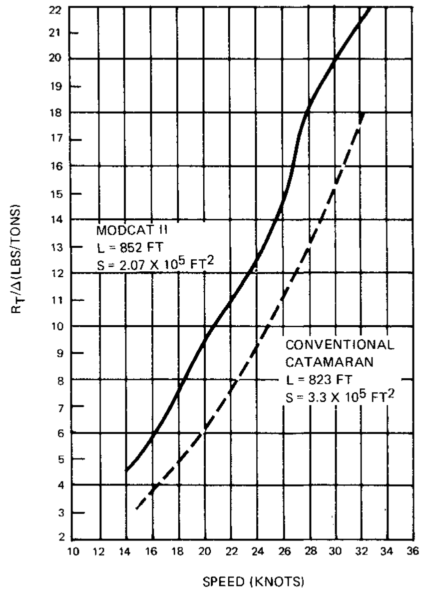

Fig. 6 Resistance characteristics for 101,000-ton displacement ships.

If the hull becomes substantially shorter and fuller and wave resistance higher, the correlation between theory and experiment may become poorer. If this should occur, then the design technique espoused previously may have to undergo further refinements, and theory on which it is founded carried to higher order. This would involve removal of the zero Froude number assumption of the Douglas program, and the use of a nonlinear free surface boundary condition in the wave resistance calculations.

Nevertheless, the approach used holds sufficient promise to reduce resistance into a regime where other properties of the LWP multihull become sufficiently attractive to make this type of ship platform attractive and competitive with other types of platforms for certain naval missions.

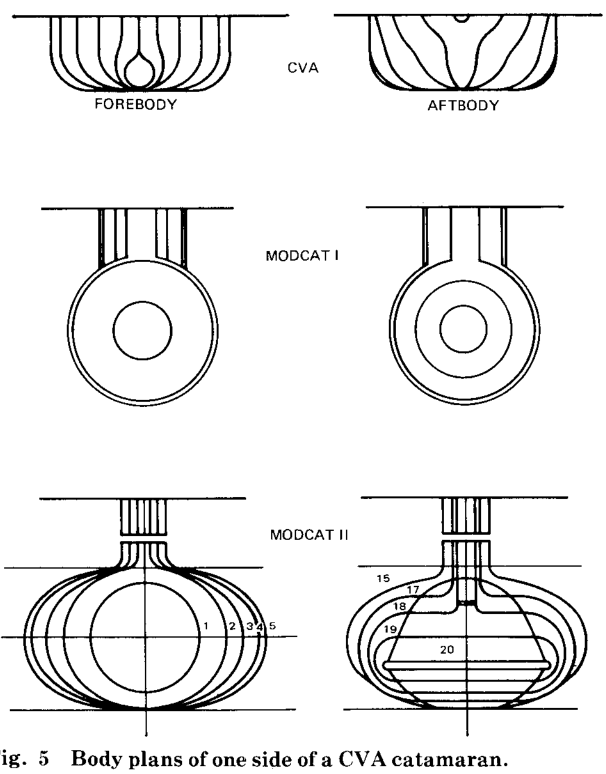

Fig. 5 Body plans of one side of a CVA catamaran.

Resistance in a Seaway

Loss of speed (as opposed to voluntary speed reduction due to slamming, etc.) in a seaway arises from combined effects of several factors, but, primarily, from an increase in resistance and a decrease in propulsive efficiency. Increase in resistance can come from wave action, ship motion or rudder action. Reduced propulsive efficiency arises from increased propeller loading due to increased resistance and to possible propeller racing or air drawing as a result of large ship motions. Although no quantitative experimental work has been done, our general knowledge from monohulls and conventional catamarans along with our knowledge of ship motions can assist in assessing possible seaway effects upon powering of LWP multihulls.

From theoretical work on added resistance in a seaway of monohulls, we know that ship motions, particularly pitch, are the primary source of increase in resistance. Wave reflection is small if there is pitch and heave motion. Since the dominant effect upon increase in resistance is ship motion, we may deduce from experience with conventional ships that loss in speed in head seas should be minimal on LWP multihull configurations. This would be due primarily to reduced motions this configuration experiences in head seas as discussed in subsection on Ship Motions that follows. Because of their high directional stability, LWP multihull require minimal rudder action to maintain course; hence, speed loss due to this cause should be very small.

Table 2 Horsepower limitations

Power train element	Now	Natural evolution
Large compact gas turbines: LM 2500	22,500	25,000
FT4C	35,000	25,000
Marinized industrial gas turbines	0	60,000
Planetary gear	35,000	60,000
Conventional reduction gears	70,000	a
Reversing gear	25,000	40,000
Clutches	15,000	25,000
Controllable reversible pitch prop	40,000	50,000
Fixed pitch propeller	70,000	100,000

[a]Limited only by manufacturing capability.

Waves become important when they impact upon the bridge structure. Longitudinal decelerations as well as impact forces can become strong enough to require a major reduction in speed. But this would happen to LWP only in sea states well above those in which it happens to monohulls. Effect upon LWP propulsive efficiency should also be negligible. A primary concern is air-drawing when a wave trough passes over the propeller. If adequate hull submergence is provided, this should not affect LWP propulsive efficiency.

Machinery

Selection of propulsive machinery for LWP multihulls presents special problems. The relatively long slender hulls place a size constraint upon major machinery components as well as upon machinery arrangements. And if its prime mover is to be gas turbines, then as with other high performance ships using gas turbines as prime mover, it must always be borne in mind that 1) the ship must be designed around its propulsion machinery, in that full load displacement is closely determined by power installed if operation near the ship's optimum drag point is planned; and 2) gaps in gas turbine sizes (powers) will cause certain combinations of ship size and speed to be undesirable.

Table 2 lists the current power constraint on each element of the power train. It is recognized that putting everything on a shaft horsepower basis is over-simplistic. However, Table 2 does present a fair picture, and that is its purpose. The column headed Natural Evolution implies that these powers can be attained, perhaps by 1979, without a special development effort, through, say, additional government financing. However, these elements may require special shoreside tests before commitment to production.

The ratings given for the LM 2500 and FT4C gas turbines are for an 80°F day, inlet pressure drop 4 in., back pressure drop 6 in. A specific design would have to use properly corrected ratings. The LM 2500 still has capacity for growth in rating as experience with it is acquired. However, the FT4C represents an upgrading of the FT4A and, as such, little future uprating is anticipated.

The Maritime Administration (MARAD) is currently funding a development program to marinize an industrial gas turbine. This engine will be rated at about 60,000 shaft horsepower (shp), but it will be considerably heavier (by a factor of about 5) for the same power than an aircraft engine derivative. While on the face of it, this engine may seem ill-suited to a weight-limited LWP multihull design, this may not be true. If the marinized industrial gas turbine has a better fuel rate than the aircraft gas turbine derivatives, the weight penalty may be offset. And, further, the controlling space factor in underbodies is gear diameter, not gas turbine diameter.

As part of the same development program, MARAD is developing planetary gear technology. Resulting gears will be capable of very large reduction ratios and will have reversing capability. Currently one 35,000 hp planetary gear with a reduction ratio of 4:1 has been developed by Curtiss-Wright. This gear was constrained by an outside diameter originally intended to fit into the nacelle of a 500-ton hydrofoil ship. It was this outside diameter which resulted in the 4:1 constraint. It is expected that MARAD's program will make larger planetary gear technology available in about three years. The largest conventional marine reduction gears manufactured to date transmit 70,000 hp.

Recently it has been impossible to persuade vendors to bid on reversing gears of greater than 15,000 hp. If such gears are desired, then a development program will have to be initiated to reduce the risk that vendors see.

The DD-963 will utilize 40,000 hp Controllable Reversible Pitch (CRP) Propellers. Such CRP propellers have been evolving to accept higher and higher powers over recent years. It is reasonable to expect 50,000 hp as feasible within three or four years. Powers significantly greater than 40,000 hp will require a special development program.

The state-of-the-art for fixed-pitch propellers is more a function of manufacturing facilities than of technology; 70,000 hp is regarded as the present limit with 100,000 hp achievable within a few years. It should be noted that the rpm/shp relationship is also meaningful. If low propeller speeds are desirable, problems in manufacturing gears, clutches, and bearings become much more critical than with application of the same power at higher rpm.

Propulsors

Since the lower portions of LWP hulls tend to be bodies of revolution, our primary source of knowledge is the single-screw submarine. This recognizes that the strut, near presence of free surface, and the other hull will somewhat modify inflow velocity to the LWP propeller(s).

From experience with submarines, it is possible to consider a number of types of propulsors for application to this type of a ship, namely, single propeller, contrarotating propellers, and ducted propellers. Since a large amount of development work is required on other aspects of LWP multihull concepts to achieve viable craft, the complexity associated with the design of the latter two propulsion systems with no significant advantages anticipated from them, precludes these systems from any prototype configuration. Therefore, only a brief treatment is given in this paper to indicate their possible application in later stages of LWP multihull development.

The contrarotating propeller system is attractive hydrodynamically. If the propellers are correctly designed to recover most of the rotational energy lost by a single-screw propeller, then it should be possible to increase propulsion efficiency by about 10% propeller-induced. It also has the advantage that the blade-frequency, propeller-induced vibratory forces are lower assuming that different numbers of blades are used on each propeller even though a greater number of frequencies will be present. Limitations for early contrarotating application are special gearing requirements. Although this gearing would be smaller than for a single propeller, its mechanical complexity of one shaft rotating inside another would be greater. Successful installations have been made.

The ducted propeller of the accelerating flow type (Kort nozzle) is also a possible candidate. They offer advantages of reduced propeller-induced vibration, less radiated noise, fuller-form hull afterbodies, and better physical protection of the propeller. The major disadvantage is the extra net weight associated with the duct. Greater mechanical and structural complexity, poorer stopping qualities, and higher directional stability of a ship which is already very stable, are additional disadvantages.

Conventional fixed-pitch marine propellers with astern turbine or reversing gear, or conventional gas turbine and reduction gear with CRP propellers are logical choices for early and prototype LWP multihulls because there is a wide base of experience with these propulsors. Their primary advantages lie in a well developed technology in the areas of propeller, shafting, and reduction gear design.

The major area of hydrodynamic investigation is the interaction of hull and propulsor to establish as high a propulsive efficiency as practicable. As indicated in Table 1, single-screw propulsion tests have been conducted only on MODCAT I and SSP, indicating propulsive efficiencies, in general, higher than those achieved on most multiscrew combatant ships. However, compared to single-screw submarines they are substantially less. This is due, on both MODCAT I and SSP, to somewhat lower values of hull efficiency (nH), the ratio of work done on the ship hull to work done by the propeller. More model propulsion and propeller wake investigations are needed to improve understanding of these lower values and how they might be improved. Once this understanding is achieved, propulsive efficiencies in excess of 0.75 should be achievable.

Propulsion experience on MODCAT I also indicates that great care is required in hull design to insure that air drawing does not become a severe problem. Wave formation of hull-strut combinations and interference between hulls must be minimal so that there is no large wave-generated trough over the propeller resulting in air drawing. It is also necessary to have the top of the hulls deep enough to insure adequate propeller submergence when the hull is responding to the seaway. Developments discussed under Ship Motions should make possible reasonable predictions, provided that the hull-generated wave train is small.

Over-all Propulsive Performance

Propulsive performance results which have been discussed are based on those actually achieved on models. In no instance has the LWP performance exceeded that of a well-designed conventional monohull. Predictions made, utilizing methods outlined previously, anticipate improved performance. Smooth-water ship comparisons have been made between MODCAT III and a very good twin-screw destroyer of the same displacement but with a 68% greater length and a 50% smaller draft. Results show that the destroyer requires about 25% less power at speeds between 30 and 40 knots. It is believed that by reducing the LWP multihull's draft and length, the smooth water difference in power performance can be reduced significantly.

As discussed previously, it would be expected that MODCAT III would show virtually no loss of speed in head seas of State 5, whereas a conventional destroyer would require about 15% more power to maintain speed in the same sea. This is assuming that the speed of the destroyer was not involuntarily reduced because of excessive ship motions. Thus, it appears that we are on the threshold where high-speed LWP multihulls can compete in power performance with comparable sized monohulls in the regime that counts, i.e., rough water.

Ships Motions

Up to this point we have been concerned with propulsive performance of LWP multihull configurations. In this section we will deal with its motion and hydrodynamic loading in a seaway and the influence these can have on design. One major difference among monohulls, conventional catamarans and LWP multihulls is the very different response of each to the same seaway. Hence, the interest in each for specific military missions.

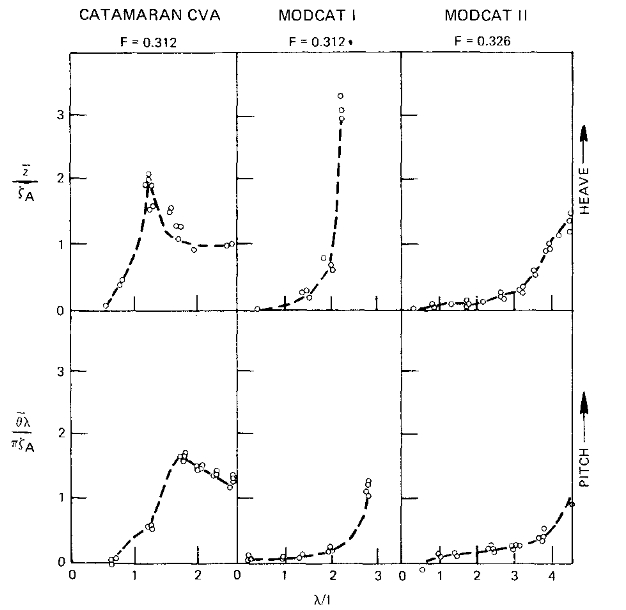

Fig. 7 Nondimensional heave and pitch parameters vs wavelength to shiplength ratio for the CVA, Modcat I and Modcat II in head seas.

Roll motion and roll acceleration of conventional ships are determined by the distance from center of gravity to metacenter, GM. If this quantity is low, roll angle will be large, but accelerations will be low. Correspondingly, if GM is large, roll angle decreases and accelerations increase. On conventional catamarans the waterplane areas together with their hull separation result in a very large GM, and therefore roll angles are small even in very severe seas although accelerations are about one order of magnitude greater than those of a monohull. The LWP catamaran offers a compromise between these two extremes. In a beam sea, roll angles can be low if hulls are widely spaced, and accelerations can be significantly lower than on a conventional catamaran.

In head seas, pitch and heave performance of conventional ships and conventional catamarans are similar for ships of the same length in the same seas, assuming that the relation of Longitudinal Center of Buoyancy (LCB) and Longitudinal Center of Flotation (LCF) to waterline length are similar. There is full scale and experimental evidence that interference effects on conventional catamarans result in an increase in pitch motion in head seas over that of the monohull. Reaction of the LWP multihull to head seas is significantly different in that both pitch and heave are substantially lower, resulting in a considerably more stable platform, hence, the high interest in this configuration.

This is most clearly shown by examining the pitch and heave Response Amplitude Operators (RAO), Fig. 7, for a large catamaran, the MODCAT I, and the MODCAT II configurations in head seas at their design speeds. From Fig. 5, which shows body plans of the three configurations, it is apparent that MODCAT I has a significantly larger water plane area than MODCAT II, and that both areas are significantly less than for the large catamaran. RAO are plotted against wave length divided by ship length, and show that maximum amplitude or resonance points shift to much longer wave lengths as water plane area is reduced, thus shifting the point of maximum ship response into the lower energy part of the sea spectrum, assuming reasonable sized ships. Hence, less motion results, or conversely, a considerably shorter LWP multihull should have similar responses to the same head seas as a much longer conventional catamaran or monohull.

Applicability of strip theory with appropriate two-dimensional added mass and damping terms for each of the

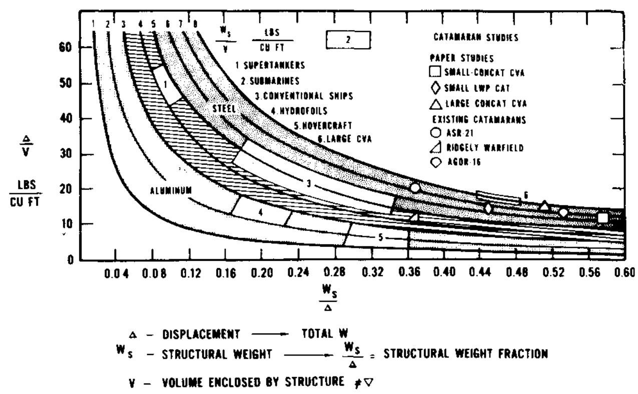

Fig. 8 Hyperbolic weight-density curves.

sections in predicting motions is well known. These have been incorporated into computer routines for predicting ship motions in regular seas; and, through linear superposition, in random unidirectional seas.[22] During the past two years, fundamental theoretical work has been done by Lee[16] on determining added mass and damping for two arbitrary-shaped two-dimensional bodies oscillating in heave. This work has correlated well with heave experiments on two-dimensional cylinders of typical displacement-type ship sections conducted by Jones. This theory has been incorporated into a computer routine for predicting pitch and heave motion of catamarans in head seas. Theory has been in good agreement with model test results from conventional catamarans. This is not completely so with the LWP multihull configuration because of viscous effects, particularly on damping magnitude. Hence, prediction of motion, particularly at resonance, is substantially greater than that measured. Much research remains to be done on viscous damping of LWP multihull type sections before reliable predictions can be made of ship motions in the resonant region. Determining motion at resonance is most important because it is likely to provide the extreme motion and hydrodynamic loads on the hulls—at least, for smaller ships.

A simple theory for roll predictions for catamarans in beam seas has been computerized.[23] It treats hydrostatic and hydrodynamic heave forces only. This routine has given good correlation on model tests conducted on conventional catamarans. It can be used for approximating roll motion and roll accelerations for LWP multihull configurations. However, it also is subject to the same limitations in calculating viscous damping effects discussed previously.

In addition to this means for solving the viscous damping problem, it is also necessary to develop a computer program for predicting pitch, heave, roll, and hydrodynamic loads for arbitrary LWP multihull configurations operating in an oblique sea. Ultimately, if advanced structural design techniques are to be used, it will be necessary to predict motion in all 6 degrees-of-freedom in a random sea, and to obtain the pressure distribution over the entire underwater body.

V. Structures

Background

Weights other than structure, i.e., propulsion machinery, electrical machinery, auxiliary machinery, and outfit and furnishings, should not vary greatly between monohulls and multihulls. Some main propulsion shafting will probably be saved in a multihull, but there will be two sets of reduction gears, particularly in the under 5000-ton ship.* In a multihull ship, almost all distribution systems (cabling, piping, internal communications, and ducting) increase in length, and therefore, in weight and installation cost compared to those of a monohull of the same displacement.†

Prime movers of support systems will, on occasion, require an increased capacity (and hence, more weight, space and cost) in a multihull because losses in the larger distribution system will require the next larger unit size of prime mover. However, aggregate effects of these and other differences should have only small variations between monohulls and LWP multihulls. Thus, for both types the disposable‡ load fraction is a function of the structural weight fraction. However, over the years through trial and error we know that a monohull's structure is near optimum within the fabrication technology used in conventional shipyards. This is not the case for LWP multihulls. Since we do not know the loadings to design to, we can not optimize its structure within the same shipyard fabrication technology.

If one accepts the aforementioned reasoning, it is apparent that the disposable load fraction of an LWP multihull ship of a given geometry is almost directly a function of its structural load fraction. Hence development in the structural area is the heart of the issue of maximizing load carrying capacity of LWP multihull ships.

There is nothing inherently more intricate about catamaran structure than about conventional ship structures. Today one could perform a structural design of an LWP multihull ship with the loads available from model basin tests. However, it becomes apparent that for every uncertainty in structural design which is off-set by a factor of safety/ignorance, valuable payload capacity (mission potential) is correspondingly decreased.

Structural density considerations are also important. If three pounds of structure per cubic foot of ship volume is achievable in all LWP applications without going to exotic materials or fabrication techniques, all our combatant ships should be LWP multihulled. If 8 lb/ft^3 is consistently achieved, the only LWP multihull ships we will see are special purpose ones that absolutely demand their peculiar properties.

These considerations are summarized on Fig. 8 where two actual conventional steel catamarans, ASR-21 and AGOR-16, one actual conventional aluminum catamaran, the Ridgely Warfield, and three catamaran studies (two conventional and one LWP) are compared with several other kinds of vessels. The ordinate is Δ/V, the ratio of displacement to volume enclosed by the structure. The abscissa is W_S/Δ, the structural weight fraction. Hyperbolas of constant structural density (structural weight divided by enclosed volume, W_S/V) are drawn. Since each class of vessels has different mission requirements, and includes vessels built at different levels of technology which probably do not correspond with levels of technology for any other class, the comparisons cannot lead to rigid results. Trends, however, are clearly indicated. For example, the catamaran vessels tend to have a great percentage of their displacement in structural weight, and a large enclosed volume for their displacement.

To make the catamaran a more desirable vessel, the

*This is not necessarily true. Unlike multihulls, in a monohull, one has the option of going to a single shaft even with two prime movers. Doing this on Patrol Frigate saved about 200 tons of shafting, foundations, associated ship growth, etc. Of course, there is a loss of maneuverability but not necessarily in reliability or survivability.

†This does not mean that a monohull and multihull would be of the same displacement if they were designed to do the same job.

‡Fixed payload (weapons, sensors, C&C equipment) plus traditional load items (fuel, aircraft, ammunition, and food).

structural engineer must move the points lower and toward the origin. In order to make structure as light as possible the use of high-performance materials is suggested. But these are the materials we know least about, and the experience needed to establish design criteria for an LWP multihull does not exist. Design loads must be determined, based on the loading spectra that the structure is likely to experience. The following sections discuss how these problems are being handled now and describe a plan for development of technology necessary for better LWP multihull structural design.

Structural Design Philosophy

There are two fundamental issues in the design of all marine structures and they are both unknowns for LWP multihull ship structural geometries: 1) Determining loadings; and 2) Once the material has been chosen, understanding how structure accepts or responds to loadings. (This is especially important at structural transitions, that is, at connections of struts to the platform, which affects choice of materials.)

Optimization cycles must then be performed consistent with other variables in the over-all design. Finally, verification of the assumptions by trials and testing concludes the process. No full-scale tests have yet been performed on an LWP multihull. Therefore, all of our information comes from analysis and/or model tests.

We are now in the process of performing the first cycle of structural design, and so no true optimization has been performed. The remainder of the discussion is devoted to load determination and usage, and discussion of two designs in steel and aluminum, and their response.

Loads

Loads applied to a marine structure can be classified as follows: 1) over-all or local: depending on whether they affect the whole structure or only a small part of it; 2) instantaneous or long-term: depending on whether one is trying to account for maximum response or fatigue effects; 3) quasi-static or dymanic: such as weight of a piece of equipment on a deck (static), hydrostatic pressure on a panel (quasi-static) or wave slam on the ship's bottom (dynamic) which, besides the impact, can set up vibratory loadings; and 4) wave-induced or not: clearly some loads exist only because of waves (motion loading, for example, or slam), while others exist even in a calm water condition (hydrostatic pressure).

Some of these loads do not depend on the shape and mission of a ship. Deck-loading, for example, for crew's quarters would be the same for a destroyer as for an LWP multihull ship. Loads that may be difficult to determine are those that depend on hull shape and mission requirements.

In trying to define these loads the first step is to determine whether traditional means of load estimating are applicable. This is desirable, since such traditional estimates include the wisdom of many previous designs, and, for surviving vessels, have nature's stamp of approval. Criticism that traditional means of estimating loads tend to overdesign, must be tempered by the concept that, due to many repetitions, designers have probably reached near-optimum conditions. By oversimplifying a little, the process is easy to describe. Traditional monohull design practice considers the ship to be a beam statically balanced on a trochoidal wave of one ship length with wave height equal to $L/20$ of the length. Other designers prefer a wave height of $1.1(L)^{1/2}$, where L is both wave length and ship length.

Loading conditions, such as light ship, full-load, etc., chosen in conjunction with the buoyancy distribution provided by the wave, result in shear and bending moment distributions. These loads, combined with the beam section modulus result in stress distributions.

Material chosen by experience is assigned a value of allowable stress. Comparing allowable vs calculated stress the designer decides whether the design is adequate. Local loads are then considered and design thicknesses locally increased where necessary. Since the material added to resist local loads usually violates the optimization process, several design iterations are usually necessary.

The traditional method, then, considers a ship to be a beam. However, catamaran geometry is simply not such that a one-dimensional analysis would be sufficient. The catamaran can not be idealized by a line (the neutral axis of the traditional ship) simply because it has two hulls and a rectangular cross-structure which may have an aspect ratio of almost 2 or even 1.5.

The designer must expect not only traditional longitudinal loading, but also a transverse bending moment from forces that tend to separate, or push together, the two hulls, and finally a torsional load from the difference in pitch of the two hulls. Therefore, a study to improve understanding of loads imposed on structure is of great importance. In order to properly design as light a structure as possible, loading must be well defined, since it is the single most important unknown. Gains can be realized in many areas. Gains that can be brought about from a better understanding of loads probably have highest potential for dramatic reduction of structural weight.

Two types of analysis are being used for load prediction: 1) static balance analysis, and 2) hydrodynamic analysis. The static balance analysis is very elementary in concept and, depending upon the assumptions, can lead to very conservative designs. It has been used extensively for the load determination for conventional catamarans, both those constructed such as the ASR 21 and for the catamaran carrier studies conducted at NSRDC described in Refs. 23, 24, and 25.

A static balance ignores pitch, roll, heave, and other motions and predicts the integrated loading on the ship due to an instantaneous balance on a wave. A computer program predicts the Response Amplitude Operator (RAO) for transverse bending moment, torsional moment, and axial force for the cross-structure. Waves were assumed to have a unidirectional Neumann spectrum of amplitudes for different ship headings. Further, it was assumed that catamarans have prismatic section.[24]

Considering all assumptions necessary to make the problem manageable, one might tend to have doubts about results. However, results predicted by the computer program seem to match the trend of the few available experimental results on conventional catamarans quite well.

Use of the static balance method for determination of loads on LWP catamarans is fraught with many uncertainties and the loads on the conventional catamaran are largely hydrostatic in origin because the hull volume is near the surface and the water plane area is large, whereas, for the LWP configuration the loads are largely hydrodynamic because of the small water plane and the relatively low depth of submergence of the main underwater body. Thus, this points to the need for obtaining the load through hydrodynamic analysis of the hulls in a prescribed seaway.

The essential ingredients exist for determining the hydrodynamic load. As shown previously in the section on catamaran motion, the basic work has been done for obtaining the added mass and damping for arbitrary shapes of two-dimensional cylinders oscillating in a free surface at various frequencies. This information is essential to determine the hydrodynamic loads at each station and, through integration over the length of the hull, determine the total forces and moments on each hull in a prescribed sea. At present computer routines are being put together to determine the lateral forces between the hulls, the transverse bending moment and torsional moment being imposed on the bridging structure for irregular head or beam seas taking into account pitch, heave, roll, and sway. This will eventually be extended to take into account all six degrees of motion and any heading into the sea. This work is the most critical of all that is underway at this writing to the successful design of the LWP multihull.

When the detailed hydrodynamic loads can be determined for a prescribed sea condition then it is possible to understand how the structure accepts and responds to the loadings using, for example, finite element analysis techniques. A crude finite element mesh has been generated for analysis of the ASR 21. This task was quite tedious and techniques are being developed for automatically generating the mesh for grillages which can be joined into boxlike structures. After that, the combination of several such boxes to form a catamaran becomes the major problem which is being attacked using advanced structures and data handling procedures.

Slamming and Whipping

A particular loading condition, which must be accurately estimated, is the set of loads which create vibration and whipping. Local loads caused by wave slamming on hull and cross-structure are being investigated by Chuang of NSRDC through use of model tests and extensions of existing theories and are not expected to be a problem. But, the vibratory response in the structure that they can cause can be serious. Preliminary investigations have shown that the over-all structure of multihull ships can be tuned as a function of the moments of inertia of the hulls and cross-structure. If this is practical in the context of a real design, this is one possible way of avoiding the vibration problem.

Materials

Mild steel is the most common material in ship building. Much experience has been accumulated on its use. High Tensile Strength steels are also well understood. As shown on Fig. 8, use of steel generally results in high density structures of 5 lb/ft^3 or more. Aluminum structures, on the other hand, generally result in densities of 3 lb/cu ft or less. The area between 3 and 5 lb/ft^3 is the area where both materials are used to help each other.

Of course, in any situation where the full strength-to-weight ratio of aluminum is being utilized, the high yield steels, HY-80 and HY-100 are very attractive.

The price that must be paid, however, for use of such high performance materials, is uncertainty and increased fabrication costs. Experience in use of aluminum is nowhere near the experience in using steels. We know even less about other materials.

Some Particular Problems of Aluminum

Aluminum has some particular problems because of lack of experience in its use. In one sense, experience is the link between the metallurgist and the ship designer. Design stress level of welded aluminum is a good example of this difference. Currently designed stress levels for welded aluminum are based not on the yield stress of the parent aluminum but on the lower yield stress of the weld. This phenomenon does not occur when steel is used. Several design choices exist.

1) Use the yield stress of the welds as a design basis.

2) Use a stress higher than that of the weld (perhaps as high as the yield stress of the parent aluminum) and expect material failure sooner thereby increasing the cost of repair. Also, to prevent catastrophic failures which may be dangerous, some sort of nondestructive testing technique must then be instituted and meticulously followed. This again, increases maintenance costs.

3) As in 2, use a design stress higher than that of the weld (again perhaps as high as the yield stress of the parent aluminum) but treat the welds after fabrication to insure such strength characteristics. Cost is increased because of the weld treatment, but the severe requirement of a nondestructive testing program is at least partially relaxed, since reliability is obtained by treating the weld.

It is difficult to assign quantitative values to such considerations at this time because experience is lacking. If we consider only one LWP multihull ship as the Navy's objective, then such questions can not be answered, and it really does not matter if they are answered. But if many LWP multihull ships are to be built, such considerations become important, since they relate mission potential, reliability, and cost per unit.

A carefully related series of analytical studies, small structural models, large structural models and full-scale experiments are required to resolve the preceding problems. An R&D Plan for such a program does exist within the Navy.

VI. Control

Directional Stability and Steering

Stability and control of LWP multihull configurations have had the least attention. Little, if any, quantitative information has been measured. Only free running tests have been conducted, and those were of an observational nature. Free model maneuvering tests in open bodies of water have been conducted on a 5-ft SSP model, and recently, by Litton on a 20-ft manned model shown in Fig. 5. These exercises have shown, not unexpectedly, that these configurations do have a large turning circle at high speeds with a small outboard heel. They also show that these craft can steer a straight course with only one driving propeller, and this with only small rudder angles. However, it was also shown possible to create a large turning moment at reduced speed by backing on one propeller and going ahead on the other, and therefore to turn in very small circles.

Two approaches have been used on LWP rudder design to date. The one on the Litton 20-ft model design and contemplated for MODCAT III utilizes rudders which are fitted to the trailing edge of the main struts, acting like aircraft wing flaps. Effectiveness of these rudders is sensitive to change in ship draft due either to changes in displacement or to changes in free surface with changes in ship speed. The second type of rudder was used on the SSP, wherein the rudder is placed behind the propeller in the slipstream. Here they are uniformly effective and not subject to effects of waterline changes. SSP rudders increase drag due to the underwater structure needed to support them.

Since no quantitative model information has been obtained to date, it is planned, on MODCAT III, to measure various horizontal plane stability derivatives on a planar-motion-mechanism and rotating arm to determine how best, on future designs, to undertake design of control surfaces to achieve desired performance. It may be possible to develop analytic methods for predicting some of these coefficients so that effects of major variations in hull geometry can be predicted.

Vertical Plane Control

In the previous section we were concerned with control in the horizontal plane of the LWP multihull configuration. The assumption made in all previous discussions is that the attitude of the craft to the free surface remains unchanged. This, of course, is not true because we have a large submerged body operating very near the free surface, creating a heave force and a pitch moment which coupled with a small water plane area restoring force can result in a significant trim angle.

In the case of SSP, this moment was so large that all movable canard-type control surfaces had to be installed in the bow, and a hydrofoil with flaps installed between the two main hulls at the stern. Vertical force and moment measurements made on the model showed large pitching moments throughout most of the speed range and a reversal of the moment as the craft went through the major resistance hump at $V/(L)^{1/2} = 1.0$. This large charge in magnitude over this small speed range is primarily due to large changes in center of application of suction forces as wave interference surfaces increase both drag and complexity of ship control systems.

Even in the case of MODCAT II where wave interference resistance is very small, the ship takes a 1.4° trim by the bow at $V/(L)^{1/2} = 1.0$. Although this angle is acceptable, it is possible that at higher speed-length ratios, even for low-wave resistance hulls, trim angle will become unacceptably large and control surfaces may have to be installed.

On none of these designs have attempts been made to predict or to measure hull-generated hydrodynamic pitching moments or heave force. This is being done on MODCAT III, where wave resistance is low, and hence available theory should be adequate.

Fortunately, there is a growing body of fundamental hydrodynamic work, looking into suction forces created by a submerged body operating near a free surface. That which is most directly applicable to this problem was developed by McCreight[27] while a student at MIT. His ensuing computer routine calculates heave force and pitch moment for an arbitrary axisymmetric body operating near a free surface in water of a finite depth. At this time it does not include the effect of the strut(s).

Correlation of predicted heave force and pitch moment with measured values will be made on MODCAT III. If pitch moment is predicted within reasonable limits, then it will be possible to determine if a trim control will be necessary. If so, the size of the system adequate to do the job can be determined.

Observation of model craft operation indicates that acceleration or deceleration can result in significant hull pitching moments due to wide separation of the center of gravity from the center of propeller thrust. The small restoring force of the small water plane area may make it necessary to devise control systems to prevent this from becoming a severe operational problem.

Intact and Damage Stability of LWP Multihulls

Because of the unusual nature of LWP multihull configurations, intact and damage stability characteristics differ from those of conventional monohulls. The LWP type is generally more sensitive to weight shifts, particularly in the longitudinal direction. Fuel distribution and consumption require careful control to prevent permanent list or trim.

LWP multihull damage stability characteristics are especially unusual. Because of the small reserve buoyancy of the struts above the waterline, any significant flooding will result in trimming or heeling until the upper box enters the water. The large volume and broad dimensions of the box then generate large righting moments, consequently further heel is small. Once in the water, reserve stability of the upper box is so large that probability of capsizing is negligible, providing there is little or no flooding within the box. In effect, there is no intermediate heel condition between the upright and box-down condition. Since high speed performance in a seaway is dependent on adequate upper box wave clearance, upper box heel will result in substantial angles. The stability criterion for monohulls is 15° heel. Both human and machinery effectiveness rapidly degrade above 15° heel. Thus a problem is presented for LWP multihull types, namely, how to limit heel, or trim for that matter, since it is also large and sensitive.

Two approaches, configuration control and moment control, are available as means for minimizing heel and trim after damage. Configuration control can be achieved by: 1) Strut flare—a 4300-ton LWP multihull ship 287 ft long with an 88-ft beam will have a 5° less heel with a 30° strut flare above the waterline. Trim can be reduced by locating the maximum flare at the ends of the ship. 2) Upper box width—increasing width of the upper box decreases the angle at which the box boundary enters the water. 3) Retractable sponsons.

Moment control can be achieved through counterflooding either by flooding empty fuel tanks or by use of clean ballast tanks. Because of restrictions on oil pollution, flooding of fuel tanks can be permitted only if fuel bags are used.

VII. Plan for Development

Objectives

The foregoing described the LWP multihull ship concept, the derivation of its principles and the status of current development. But, what should be done next? This section will lay out an outline for a suggested development program and the rationale behind it. A guiding philosophy behind this section is that the LWP multihull concept can be developed with existing off-the-shelf technology and hardware. The system as a whole, however, must be designed and demonstrated.

Typical problem areas which require the attention of this philosophy are: control of the vehicle in the vertical plane in seaways, propeller-hull hydro-elastic interactions, and the construction of an optimized structure. In addition, compatibility with likely payload items, e.g., sonars, helicopters or vertical takeoff and landing aircraft, must be demonstrated.

There are two aspects to the development program: 1) the kinds of ships we are trying to make feasible, and 2) given the kinds of ships, the program to achieve feasibility.

Two types of ships identifiable at this time as objectives of the development program are next generation Patrol Frigate of about 4000 tons and a next generation Sea Control Ship in the 10,000–20,000 ton range.

To achieve these objectives, i.e., fleet ready LWP multihull ships, a development program, Fig. 9, is needed now. Figure 9 is reasonably self-explanatory and will not be elaborated on further. However, the rationale for why a development program is required must be stated and the rest of this section is so devoted.

There is no reason why we could not start design of an operational 2000–5000 ton LWP multihull ship right now. All machinery required is in the range of current equipment being manufactured. A structure could be designed which is safe, although it would not be known how optimal it is. And a system to control vertical plane motions could be designed using current antiroll stabilizer technology. Then why do we need a development program?

The answer lies mainly in three requirements: 1) Design and construction risks must be reduced to a reasonable level. This includes a demonstration that the ship system as a whole will function in a real environment. 2) Suffi-

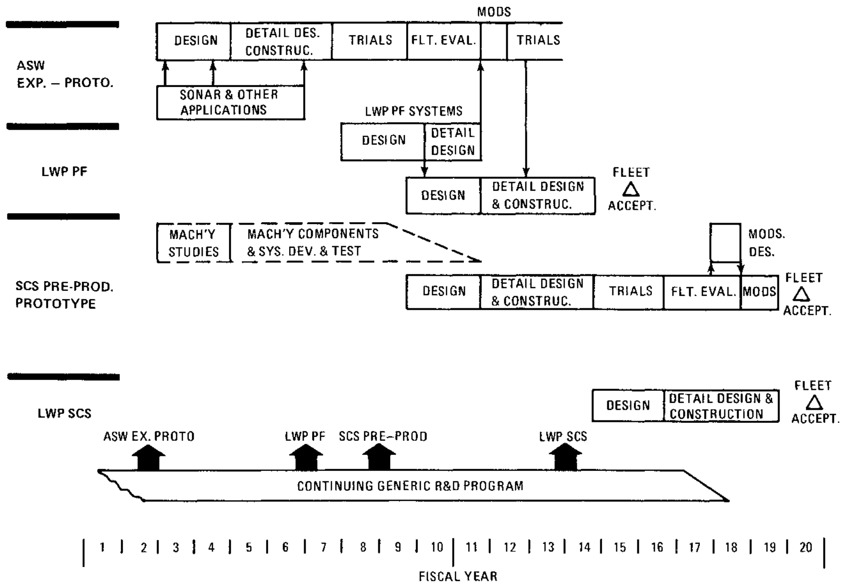

Fig. 9 Low risk LWP multihull ship system development program.

cient subsystem technology must be developed in order to optimize design of future LWP multihulls. 3) Operational advantages of LWP multihull ships in service applications will be discovered only when a prototype is available for fleet use.

Given that the above three requirements are sufficient justification for a development program, then what must such a program include? Basically two things: 1) a prototype ship, and 2) a broad technology development effort.

Why a Prototype?

How does a prototype satisfy the preceding three requirements? Clearly, without a prototype, operational experience required to discover new operational applications could not be obtained. In addition, certain full scale tests are necessary to corroborate theory and laboratory experiments, since subsystem technology necessary to do tradeoff studies lacks credibility until verified full scale. Five such areas exist: 1) complete structural load determination if three-dimensional seaways are measurable at the time the LWP experimental prototype is tested, otherwise head, beam and following seas structure load determinations; 2) how the structure works to accept its loadings (both instantaneous and in fatigue); 3) full-scale resistance prediction; 4) prediction of the flowfield that the propeller sees; and 5) motions, open loop dynamic stability, and closed loop (controlled) dynamic stability.

Finally, and most importantly, it is unlikely that a class of ships would be committed to the LWP multihull concept without having had a reasonable large one already built. This is because putting it all together and having it work is an area filled with "unk-unk's" (unknown unknowns). Since unk-unks are by definition not describable, only certain possible problem areas will be listed: 1) building large flexible structures in conventional shipyards, without going to sophisticated fabrication techniques which would drive prices up; 2) machinery and other alignment problems in such flexible structures; and 3) vibration and other hydroelastic problems whether propeller, machinery or shock-induced.

A side benefit of having built a prototype is that cost data would become available which would provide the basis for a cost estimate for a class of LWP multihull ships. Thus, the prototype makes an essential contribution to satisfaction of all three requirements which a development program must meet.

Why a Technology Development Program?

Technology development addresses the first two requirements of the over-all development program. First and foremost, the technology development program must provide the basis for tradeoff studies and design optimization. Without a broad data base, ship system designers will be "in irons" when the Navy wants to capitalize on a successful experimental prototype. As was seen earlier, an extremely meager data base in structures and hydrodynamics exists. Only sufficient data exist in the hydrodynamics area to indicate the concepts potential in resistance and motions areas. Practically nothing useful exists from the viewpoints of propulsion, maneuverability, stability, and control. The structural area consists of largely incomplete paper studies. A complete theoretical and experimental research and development program must be launched in both structural and hydrodynamics areas to provide the broad data base required.

Technology development also supports minimization of design and construction risks. It does this in general by laying the basis for design. But, in particular, it addresses several special problems, such as: 1) design of structural details crucial to use of aluminum, and 2) design of propellers to minimize possibility of propeller induced hull vibrations in the relatively flexible structure.

More detail on current status of and future plans for generic technology development for LWP multihull ships was described in Recent Results and Current Work.

VIII. Summary

General

In this paper we have attempted to show the potential of the Low-Water Plane (LWP) multihull concept. Compared to conventional monohulls, it promises a relatively motionless ride in seaways. Further, it promises to have less resistance and higher propulsive efficiency at the top of and just beyond the normal speed range of conventional monohulls. This ought to be especially true in seaways where predicted speed loss due to additional resistance and loss of propeller efficiency is expected to be considerably less than for a conventional monohull.

Because of these particular advantages it is anticipated that the LWP multihull concept can be the one preferred for relatively fast ships from PG and PF size to the size of the next generation Sea Control Ship, which is presumed to be less than 20,000 tons.

Conclusions

To bring the concept to successful fruition requires an all-out development effort as described in Plan For Development. Briefly, this program amounts to following these recommendations: 1) Embark immediately on development of a 2000 to 5000-ton experimental prototype for an ASW-oriented LWP multihull including an appropriate sonar effort. 2) Embark immediately on a propulsion system engineering development program aimed at a 10,000 to 20,000-ton Sea Control Ship. 3) Make a substantial commitment to a continuing generic R&D program which supports development of the LWP multihull concept as described in Recent Results and Current Work. 4) Initiate design of both an operational LWP PF and a Pre-Production Prototype LWP SCS before the close of this decade.

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