HIGH PERFORMANCE SHIPS - PROMISES AND PROBLEMS

Owen H. Oakley
Bureau of Ships, U.S. Navy

The U.S. Navy's interests in ships of maximum performance as regards speed, motions, and quietness are discussed from the point of view of design and application. A number of exploratory studies, and the designs of developmental craft, are reviewed in this light. The promise of each is considered in regard to the compromises required and the problems encountered in the course of development. It is concluded that, while no dramatic "breakthroughs" are foreseen, the accelerated pace of research in ship hydrodynamics will produce significant changes in the shape and performance capabilities of naval craft in the next few years.

INTRODUCTION

The United States Navy is currently engaged in the study of a variety of design concepts, some of which differ sharply from the conventional shape of ships. It is my purpose to describe and discuss the pattern and direction of these efforts, less from the standpoint of hydrodynamics than from the overall viewpoint of naval ship design.

If this viewpoint appears sometimes to emphasize the problems rather than the promises, it is because it is the daily experience of design that the problems are often obscured by the rosy glow of the promises.

Many of our present-day naval and merchant ships are a result of a slow process of evolution. New designs have been based on previous successful ships; small modifications were made to accomodate new needs. However, in recent years, it has become evident that a new, fresh look was desirable. Modern technology presents greater capabilities in power plants and electronic equipment. Basic research has given a better understanding of ship environment and ship behavior in that environment. The question is being raised more and more as to whether we need adhere to many of the compromises that have traditionally made up standard design procedure. The need for high performance in ships is pressing and the time is right for reappraisal of basic concepts.

Exploratory studies of the type under discussion may follow one of three paths. One approach is to select a single facet of ship behavior and try to optimize it. Necessary compromises are then made with an eye toward retaining as much of the original gains as possible. Another method is to examine closely and carefully new and hitherto neglected scientific achievements which may only lack development to bring them to the point of usefulness. The third method is to take an overall look at various ship missions, pinpoint the major problems, outline broadly the possible solutions to these problems and then develop the most promising. The high performance ships discussed in this paper are products of all three methods.

At the risk of oversimplifying, we can state that there are three principal reasons for exploring unusual hull forms as they apply to naval craft: to increase speed, to minimize or control motions, and to improve stealthiness. The first two are neither new nor peculiar to naval ships; men have been concerned with speed since the first log canoe and with motions since the first case of mal-de-mer. The third feature, stealthiness, was concocted to cover the functions of detection, localization, and classification of the enemy ships while remaining immune to detection, localization, and classification by the enemy. One of the major components of stealthiness is hydrodynamic quietness. This is a relatively new goal in ship design and is, of course, important where sonar performance is concerned.

The three qualities of speed, motion, and quietness are obviously not independent, so that changing one changes the other two. It appears, sometimes, to be a fundamental law of nature that maximizing one quality usually results in degrading others. In a few cases this did not occur; these are exceptions and like all good exceptions only go to prove the rule.

The phenomenon of surface waves is one of the more interesting properties of water. In a sense it is the subject of this symposium, since it is by the avoidance or minimization of wave effects that we hope to maximize speed and seakeeping performance. The energy absorbed in the creation of surface waves to a large degree limits the speed of surface ships. Likewise, it is the energy imparted to the ship by surface waves that limits other aspects of ship performance. Quite naturally, therefore, exploratory studies have been directed primarily at avoiding or minimizing these surface wave effects.

Fig. 1 illustrates a range of concepts and relates them to the free surface. In the top group, two methods of avoiding the free surface are indicated, in the middle group the avoidance is less complete, while in the bottom group, two surface ship hull forms are shown which are designed to cancel wave effects rather than avoid them.

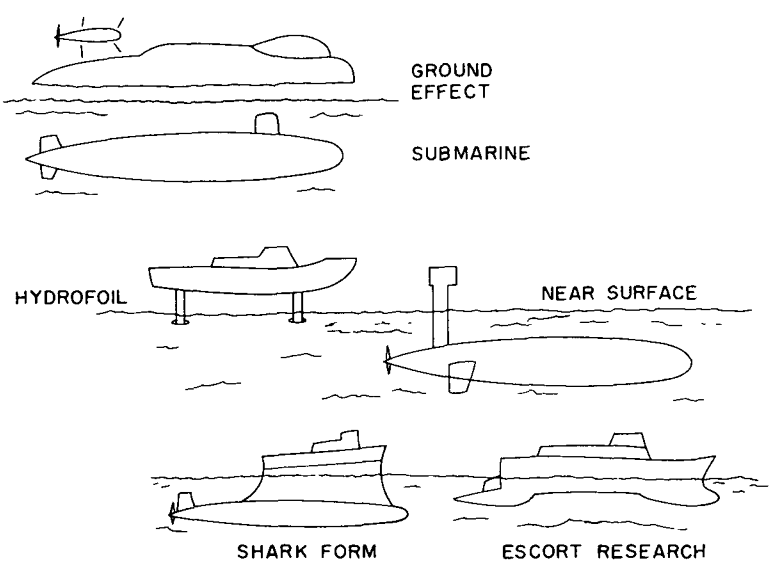

Fig. 1. Various high performance ships

This paper will discuss the potential of these concepts and some of the problems that arose in expanding certain of them into practical ship designs.

SOME HIGH-PERFORMANCE SHIPS

Ground-Effect Craft

Ground-effect craft offer the contradictory capabilities of high speed and the ability to hover above the surface. Speeds of well over 100 knots appear to be attainable and such speeds are attractive for many applications. The ability to hover has obvious advantages, for example, in amphibious operations. Recent theoretical and experimental evidence indicates that in the high speed range of operation, these craft will not respond to wave action, but can maintain level flight over ocean waves. These promises, when and if attained, indicate applications for amphibious warfare, antisubmarine warfare, aircraft carriers, missile carriers, cargo and personnel carriers, etc. The rapidly expanding literature on these ground-effect craft is a measure of their apparent promise; it is also a measure of the many problems to be resolved.

Ground-effect craft do not completely avoid the free surface, particularly the more "pedestrian" versions of this concept. Fig. 2 shows four types. Various combinations of these basic schemes are possible, and it would seem that every conceivable variation has been proposed.

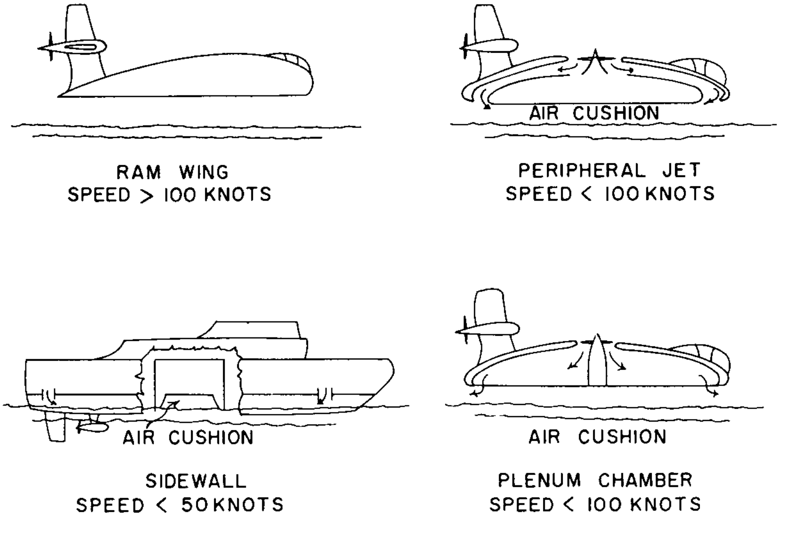

Fig. 2. Four forms of ground-effect craft

The "ram wing" shown in the top of Fig. 2, is actually a low-flying aircraft. The significant reduction in induced drag achieved by flying close to surface should permit the attainment of very high lift/drag ratios at high speeds. Values as high as 60 at a chord/height ratio of 0.5 have been estimated.

The two bottom illustrations of Fig. 2 have received a great deal of attention. The literature is too extensive for complete reference here; the International Symposium at Princeton did present, however, a substantial cross section of the efforts going on in the world.

A large percentage of the research effort has been applied to the peripheral jet type. In this case, air jets are located along the periphery of the craft. When starting, the jets hit the water, and split, part of the jet goes inward and is trapped. The pressure in the air cushion is thus built up. Equilibrium is reached when the pressure in the air cushion is sufficient to bend the jets so that no more air goes inward. A simple analysis indicates that the required lift power for a particular craft depends on the weight of the craft times the velocity in the jet for a constant jet momentum. If a heavy fluid, such as water, is used instead of air, constant jet momentum implies a higher mass flow and a lower jet velocity and thus lower required lift power. Air, for the air cushion, must be supplied separately; the water curtain simply provides the seal to contain the air.

The amount of power required to supply the air cushion is a function of many parameters; among the most important is how high the craft flies and the peripheral length of air seal. Flight over water permits the use of sidewalls extending into the water (lower left in Fig. 2). The air loss can be greatly reduced by this device. The penalty for this is lower speed and loss of ability to "fly" onto a beach. The drag of the sidewalls apparently limits this type to about 50 knots, beyond which the peripheral jet offers a more efficient use of installed power. Fig. 3 shows in a highly qualitative manner the relative speed/horsepower characteristics for the four basic types.

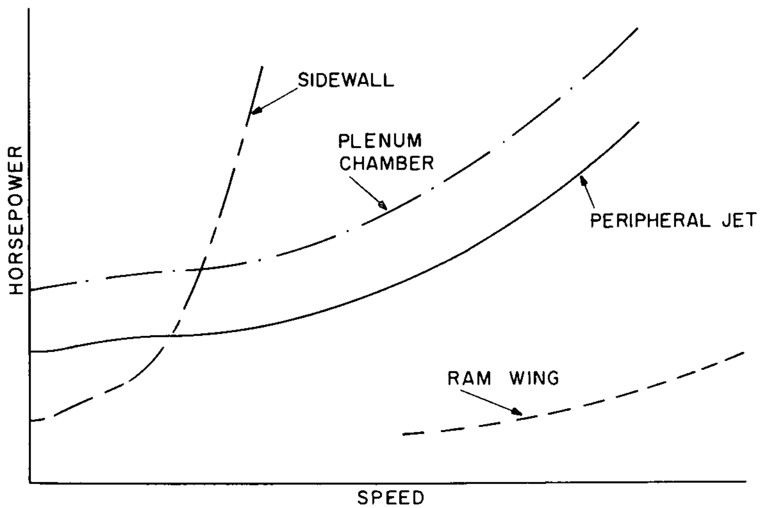

Fig. 3. Speed-power curves for the four forms of ground-effect craft

The problems to be solved are numerous. As implied by the previous discussion, most of the past efforts have gone into the determination of the mechanism and parameters affecting hovering. An examination of dynamic effects associated with forward motion has just recently begun.

The ram wing will encounter all the problems of takeoff, landing, and in-flight control of ordinary aircraft, plus the precise control required in flying close to the surface. Take-off or low-speed power requirements may well prove to be governing.

Stability and control behavior over waves is not well understood. Tests to date indicate problems associated with running trim even in calm water. Theoretical insight is being gained into the mechanisms of damping and resonant frequencies of motions over waves, but this is not complete, nor do we have as yet very much experimental experience.

The scaling laws are being carefully examined, especially in light of the British experiments with "hovercraft." Here, for example, large scale tests indicated severe spray problems, which did not arise in the small scale model tests.

The dynamics of water-wall craft have not been examined extensively. How can we reduce air leakage through this water screen? We know that the screen is relatively good at short distances down from the jet exit, but leakage is severe at substantial heights before the jet hits the free surface.

In all of these craft, a major problem is how to design the light structure required and still retain the ability to land and rest on the water in waves. Aircraft structure would be too light to meet the landing in waves requirement, while standard ship structure would be so heavy as to eliminate any payload. A blending is required.

Light-weight, high capacity air fans are required that will operate against the high cushion pressure that is needed for ground-effect craft. It is estimated that for large, operational ships this back pressure may be in the order of 150 pounds per square foot. Such fans are not shelf items.

From the designer's viewpoint, the promises are meaningful and the problems do not appear insurmountable. However, considerable expenditures of research effort and time are required. U.S. Navy work in this field, is aimed at the construction of a large ground-effect vehicle about 1963. The size and type await the results of research now underway.

Submarines

Just as the aircraft flies high and eliminates surface effects, the submarine departs from the free surface by submerging. Undesired motions are reduced rapidly with departure from the surface because wind-formed waves attenuate quickly with depth. Speed is also benefitted because it is no longer limited by the creation of surface waves. The submarine offers the ultimate in stealthiness. Thus, its principal promises are high speeds and a high degree of undetectability.

Fig. 4 shows a comparison of the power to drive two hulls of about the same displacement where one is a modern submarine and the other a destroyer hull form. Part of the submarine's advantage is its much superior propulsive efficiency. The remainder of the difference is largely attributable to the elimination of wave resistance. These two effects more than balance the greater frictional resistance of the submarine which results from its greater area of wetted surface.

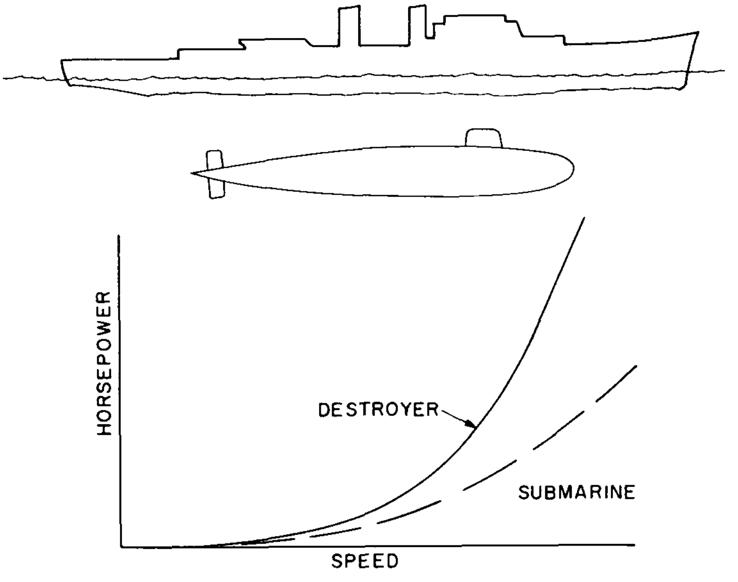

Fig. 4. Speed-power curves for a submarine and a destroyer of about the same displacement

Fig. 5 shows a comparison between the pitching motion of a submarine on the surface in a moderate sea state compared to the submerged pitching. The data is presented in spectral form and shows the large decreases in motions for fairly shallow submergence. (Note, however, that the ordinate is proportional to the pitch amplitude squared.)

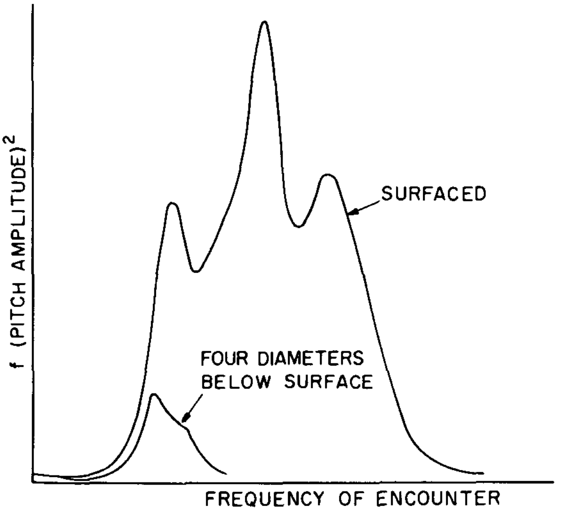

Fig. 5. Energy spectrum of the pitch amplitude for a submarine

Within the past 10 years technological advances have been exploited to make the submarine the most fantastically mobile and powerful warship yet devised.

The foregoing are all promises realized, but progress in improving the performance of submarines still encounters problems. The problems essentially consist of a search for methods of improving this already powerful vehicle. The most significant improvement would be to increase speed. The most direct way, of course, is simply to increase the power. This would require a larger hull, so that some of the gain would be eaten up in added frictional resistance. A simplified parametric study holding payload constant and using present specific weights and volumes for machinery, indicates that a submarine would require well over 100,000 shaft horsepower to attain 50 knots. This is right at the upper bound of present technology as regards the power that can be absorbed by a single propeller. Improvements in specific weights and volumes of submarine power plants will naturally improve this situation, but it is apparent that dramatic increases in speed will be hard earned. Other methods of improvement, such as reduction of resistance by boundary layer control will be discussed in a later portion of this paper.

Near Surface Craft

The near surface craft is intended to combine the stealthiness, speed, and motion characteristics of a submarine with the air-breathing, air-communication aspects of the surface ship.

At present, nuclear power plant weights are extremely high compared with the more advanced air-breathing plant. If the submarine could be run sufficiently close to the surface to breathe air through a slender strut, and still stay far enough down to avoid excessive wave drag, a lightweight air-breathing plant could be used.

The near surface craft is intended to do this. Work on this type is currently being performed by the Davidson Laboratory. Fig. 6 shows a series of speed-power curves, as a function of depth of submergence, for an arbitrary submarine type hull form. In order to

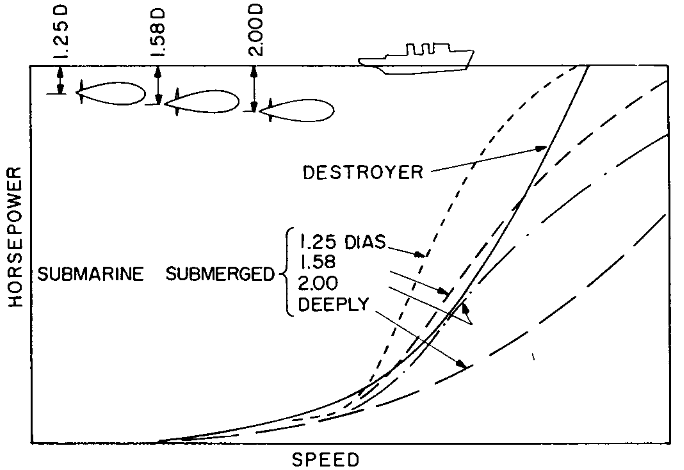

Fig. 6. Effect of the depth of submergence on the speed-power curves for a submarine

compete with a destroyer hull form of equal displacement, the near surface craft must travel below a depth of about one and a half diameters to the axis. This implies a strut length somewhat greater than one hull diameter plus additional length in order to project some distance above the free surface to allow for waves and depth control variations. Such a strut must carry at least a periscope or closed circuit TV camera unit, communications and radar antenna and a snorkel head valve. The size of the air passages appears to govern the size of the strut. For a 20,000 shaft horsepower installation, some 80 square feet of intake, exhaust and ventilation duct is needed. This results in a strut with a chord of some 26 feet and a thickness of 6-1/2 feet, altogether not a small structure. The resistance of this strut would degrade the speed performance and affect the stability and control.

Just as the ram wing needs controls like an airplane, the near surface craft needs controls like a submarine. In fact, the controls have to be more effective to counter the effects of surface waves. Also, the structure would have to be sufficiently strong to withstand accidental deeper submergence.

Hydrofoil Craft

Hydrofoil craft promise primarily high speeds. It appears likely that speeds in excess of 100 knots are possible. In addition, motions in a seaway should be considerably less than buoyant craft of the same displacement. These craft can maintain high speed in sea conditions considerably more severe than would compel a displacement craft to slow down.

The United States Navy has maintained a hydrofoil program since shortly after World War II. Out of this has come considerable research and development, and a number of test craft embodying some promising principles. Four of these are shown in Figs. 7, 8, 9 and 10.

Fig. 7. A test hydrofoil craft, the Baker "High-Pockets"

The Baker boat, "High Pockets," exemplifies the use of surface-piercing foils (see Fig. 7). This craft has the feature of essentially equal distribution weight on the forward and the after foil systems. The Carl XCH-4 (see Fig. 8) embodies ladder foils, an "airplane" distribution of foil area fore and aft, and air screw propulsion. The Miami Shipbuilding Company's "Halobates" (Fig. 9), utilizes submerged foils in an "airplane" distribution and a right angle drive over the stern. Control in the version shown was achieved by the "Hook" system which

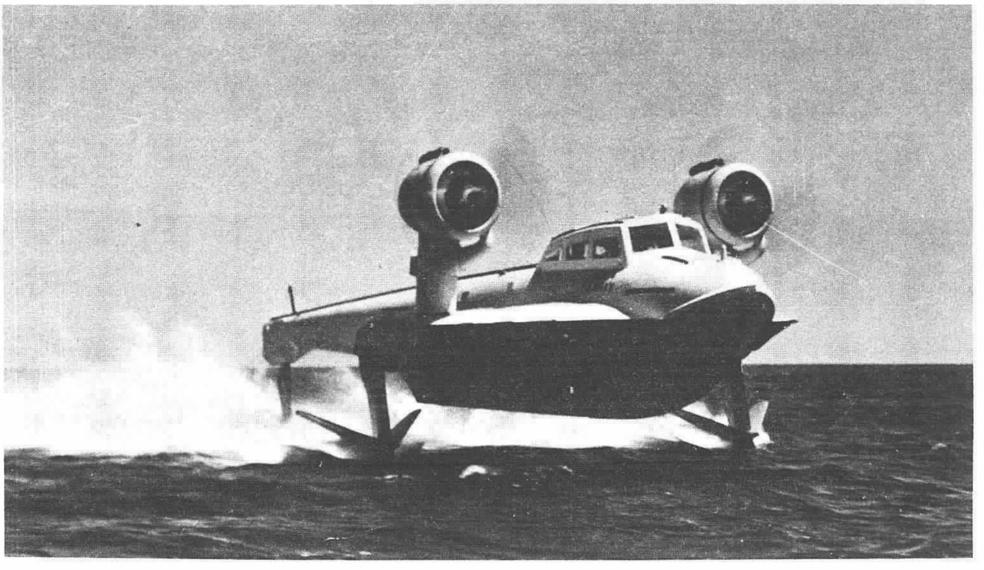

Fig. 8. A test hydrofoil craft, the Carl XCH-4

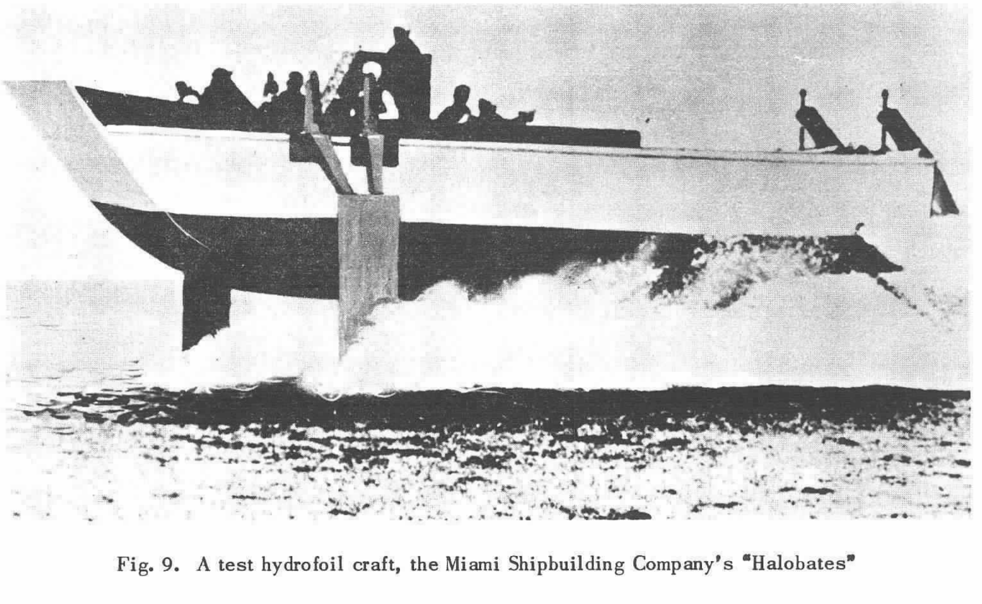

Fig. 9. A test hydrofoil craft, the Miami Shipbuilding Company's "Halobates"

used mechanical "feelers" to sense the waves ahead of the boat, and which, through linkages, adjusted the angles of attack of the forward foils. This craft was also successfully operated using a resistance height sensing device on the forward struts and an electronic "hydropilot" The most successful of these craft was "Sea Legs," by Gibbs and Cox, shown in Fig. 10. "Sea Legs" has submerged foils in a canard arrangement and a sonic height sensing system which actuates the control surfaces through an autopilot and hydraulic servos.

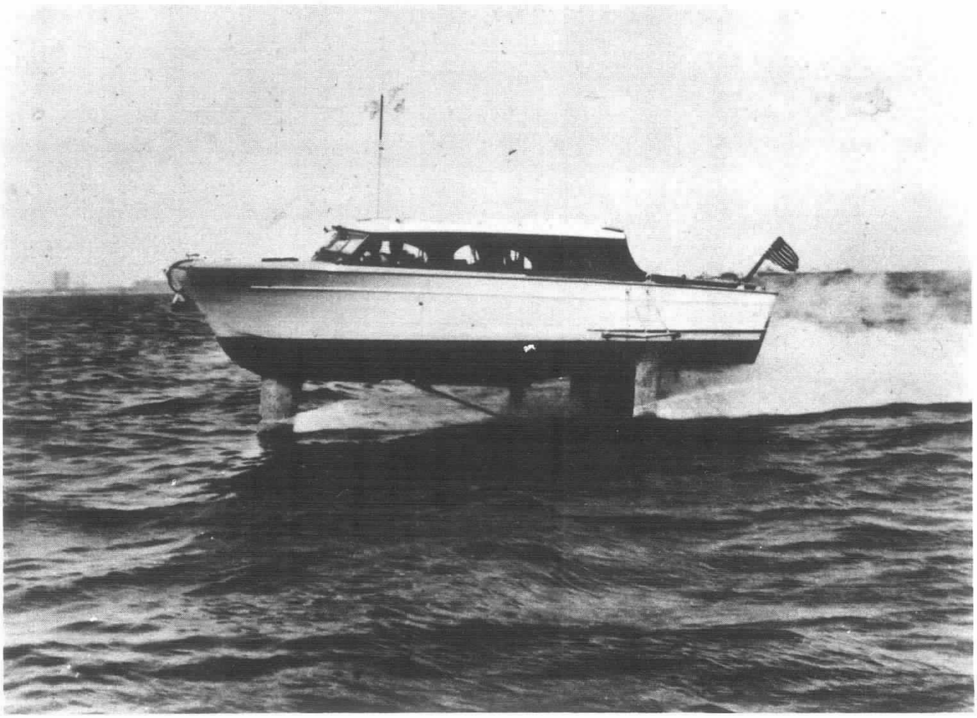

Fig. 10. A test hydrofoil craft, the Gibbs and Cox "Sea Legs"

Based on the successful performance of "Sea Legs" the submerged foils-autopilot system, was used for the antisubmarine hydrofoil craft "PC(H)." Fig. 11 shows an artist's concept of PC(H), for the construction of which a contract has recently been awarded to the Boeing Aircraft Co.

These craft are all of the subcavitating type. The maximum speed for subcavitating craft for all practical purposes is limited by cavitation to about 55 knots in calm water. It should be noted however that the XCH-4 attained a speed of about 65 knots. This craft, however, was overpowered and lightly loaded, so that any added drag due to cavitation was probably not limiting. In rough water, wave orbital velocities induce variations in the angle

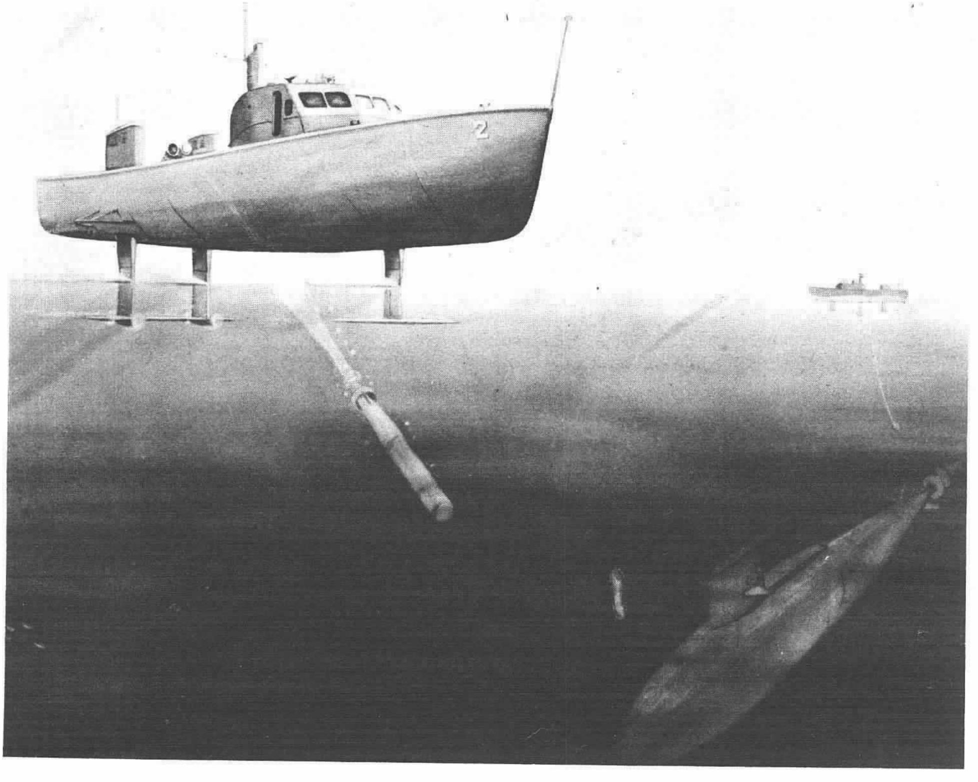

Fig. 11. Artist's concept of the antisubmarine hydrofoil craft "PC(H)"

of attack of the foils, which causes cavitation to occur at lower speeds. Fig. 12 shows the variation of angle of attack with craft speed for a state 5 sea. Fig. 13 shows the degradation of cavitation-inception speed with increasing wave height for a thin hydrofoil. Considerable work has been done on section shapes to delay cavitation, but only limited gains are possible in this direction. If we are to attain the promise of high speeds, it must be by utilizing supercavitating sections.

In the supercavitating regime we find that very high speeds or large angles of attack are required for true cavity flow. In practical foil configurations, the cavity is likely to vent to the atmosphere, either through tip vortices or down a strut. This leads to the conclusion that superventilation rather than supercavitation is the more practical mechanism to consider.

It appears that in the subcavitating range we may expect overall lift/drag ratios of about 9 to 12, and in the superventilated range, lift/drag ratios of about 5 to 7. While the lower lift/drag ratios require more power and demand more economy in structural and other weights, this does not appear to be prohibitively restrictive.

In the course of designing PC(H) a number of problems were successfully resolved on paper, while others required considerable test and reevaluation effort. For example, calculated predictions of lift and drag at top speed were in close agreement with model tests.

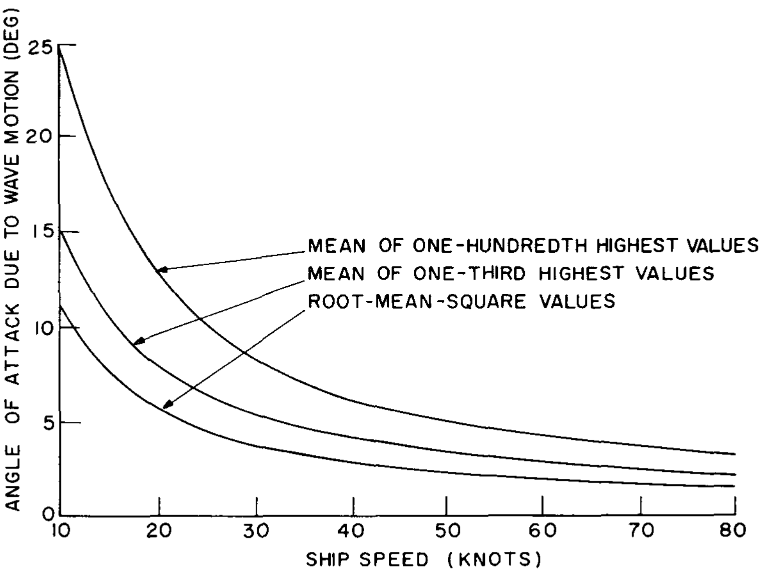

Fig. 12. Variation of the wave induced angle of attack for a state 5 sea and a hydrofoil 5 feet below the surface

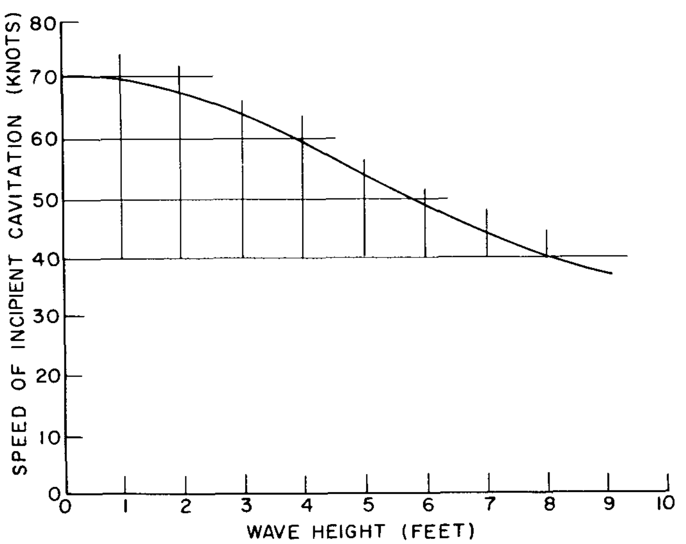

Fig. 13. Degradation of cavitation-inception speed with increasing wave height for a thin foil submerged 6 feet and a wavelength of 100 feet

This result confirms our confidence in the use of the extensive airfoil data that are available. Model experiments in takeoff drag and available thrust indicated satisfactory margins. It was found, however, that very poor flow conditions existed at the intersection of the strut, foil, and nacelle. This poor flow was found to be cavitation and not separated flow. In analyzing the problem, aircraft technique was borrowed and simple consideration of adding pressure distributions led to small changes in configuration; the resultant clean flow was confirmed by experiment. The PC(H) represents the first hydrofoil for which the hydrodynamic coefficients were obtained experimentally at the David Taylor Model Basin. These coefficients are needed for determination of stability and autopilot gains for vertical-plane motion. Horizontal-plane and coupling effects are planned to be obtained in a similar manner in the near future.

A few problems remain to be resolved in the subcavitating regime. Probably the major one is the determination of the hydroelastic dangers, i.e., flutter and divergence. There is no adequate theory for prediction of instability speeds, and practically no experimental work in the marine range of interest. The flow problems at the intersections of strut, foil, and nacelle need to be codified. Flap effectiveness at low submergences (as determined from PC(H) tests) appears to be less than predicted by theory. These problems are all currently under study.

Flying qualities in waves are being examined. In very high speed hydrofoil craft (70 to 100 knots), the frequency of encounter with waves will be so high that it will be impossible to "contour" the surface without inducing excessive accelerations. This implies the necessity for "platforming;" that is, the craft's trajectory must remain essentially horizontal. This further implies submerged foils, because surface-piercing systems cannot platform. In addition, long struts will be needed to keep the hull clear of the water and yet insure continuous good submergences for the foils in rough water. In order to platform, the autopilot system must move the control surfaces continuously and at rapid rates in order to nullify the wave-induced disturbances. In some following seas it may not be desirable to platform and here the control system will have to permit some vertical motion. This suggests not only a wave-height sensing device, but also inputs to the autopilot from accelerometers. Roll control will require additional displacement, velocity, and acceleration inputs.

The major problems to be resolved are primarily in the supercavitating regime. Here we have theory to guide us, but systematic experimentation on the effect of geometric characteristics of foils is lacking. There are no corresponding airfoil data, of course, that are useful.

As indicated earlier, the mechanisms of ventilation are not well understood and require research starting with the basic physics of the phenomenon.

A simplified theory of hydroelastic instabilities has been developed, but there are no experimental data. This theory, incidentally, indicates a greater likelihood of hydroelastic instabilities than for a comparable all-wetted hydrofoil. Also, advances are sorely needed in materials in order that the requirements in hydrofoils for very high strength, erosion, and corrosion resistance, toughness, good fatigue life, etc., may be met.

In the supercavitating or superventilating range, takeoff may well be critical. Feasibility studies have shown that for very high speed craft, takeoff thrust requirements are incompatible with top-speed requirements. Means for achieving takeoff at lower speeds need special attention.

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Foil smoothness is, of course, vital to good performance. Present tests indicate that paint (both anticorrosive and antifouling) is likely to peel off at high speeds. One promising approach is the Cox System of cathodic protection. In this method, high current densities are applied when the boat is motionless in the water. This plates out a combination of magnesium hydroxide and calcium carbonate on the foils. The idea is that the fouling will attach to this rather soft coating, and slough off at reasonably low forward speeds. A minimum value of current density is applied at all times to eliminate corrosion.

The Navy's present activity in the hydrofoil area includes an extensive research and development program directed toward a large experimental subcavitating hydrofoil ship of about 300 tons displacement and a small superventilating hydrofoil boat (about 15 tons) to be in operation by 1963.

Shark Form

If we do not try quite so hard to avoid the free surface, and if we acknowledge that certain armament and surveillance activities require topside space, then it is not a long step from the concept of near surface craft to the shark form of Fig. 1. In effect, this is simply a near surface craft with a relatively large strut piercing the surface. The shape and location of this large strut should be such as to cancel as much of the main hull's wave resistance as possible and reduce the exciting forces and moments due to sea action. Thus, the promises of the shark form are high speeds and small motions.

This concept was explored to some extent by the Germans during World War II, and this resulted in the Englemann craft. This form should have favorable motion characteristics, especially in head seas, because of the long natural periods of pitch and heave, which result from the short, fine waterline.

Fig. 14 shows a comparison of the shark form and a destroyer type hull form. At the lower Froude numbers, the shark form is quite resistful; however, at high speeds, the shark form is better than the destroyer form.

There are a number of problems to be resolved before the promises of this form can be realized.

As shown in the case of the near surface craft, the submerged hull must be located well below the free surface in order to minimize wave-making resistance and the exciting forces of the sea. In common also with the near surface craft, the shark form requires power plants of less specific volume than currently available in order to attain the speed-power advantages shown in Fig. 14.

The amount of topside weight which can be carried is limited by the low transverse stability. With very little waterplane, stability must be attained by keeping the center of gravity below the center of buoyancy. This is not easy in a form such as this, in the face of the demand for topside locations for equipment.

The shark form has, in common with the ground-effect craft, a problem of running trim in calm water. Fig. 15 compares observed trim tendencies at zero angle of attack with those calculated from Pond's theory for Rankine ovoids. This comparison is, of course, not strictly valid because of the difference in submerged hull shape and the fact that the theory does not take into account the topside shape of the shark form. Even so, the trends do

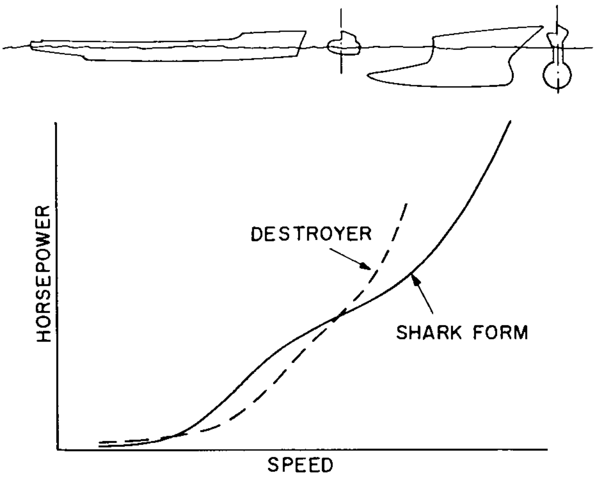

Fig. 14. Speed-power curves of a destroyer and the shark form

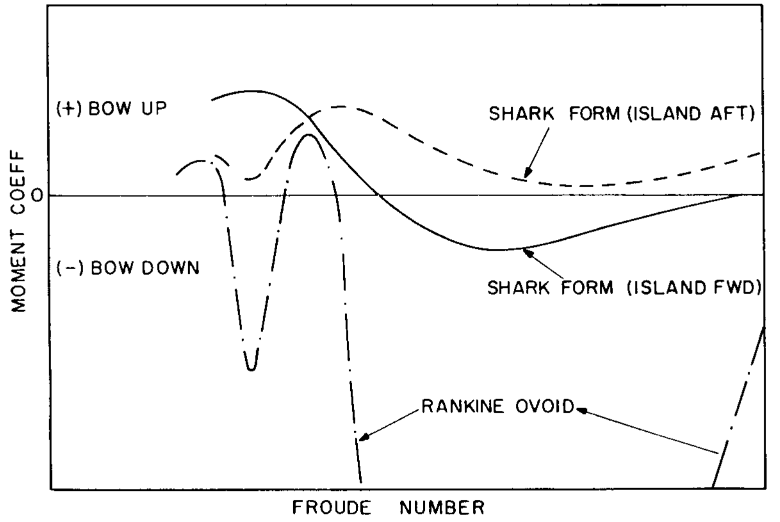

Fig. 15. Comparison of the pitching moment for the shark form with Rankine ovoids, with the hull 1.5 diameters below the surface

appear comparable. The pitching moments are not small and will probably require large control surfaces to counteract them. In view of the fact that the moments vary in direction and magnitude with speed, the control surfaces may have to be controlled by an autopilot system.

Escort Research Ship

The escort research ship (see Fig. 1) is an actual design which was prepared to provide a research vehicle emphasizing quietness and minimum motion. Hydrodynamic quietness was sought by using a lightly loaded propeller and locating it deep and at the end of a nacelle well removed from the influence of the hull. Fig. 1 also shows the large nacelle or dome located at the bow to house sonar transducers and to provide damping and added mass which tend to produce favorable pitch characteristics.

The aim of this unusual hull form was to avoid resonance in pitch by raising the natural pitch period. It was hoped by this to permit operation in the supercritical region with attendant low pitch response. This is illustrated in Fig. 16, which shows a single degree of freedom type of response for a damped system and indicates the supercritical range in which it is desired to operate.

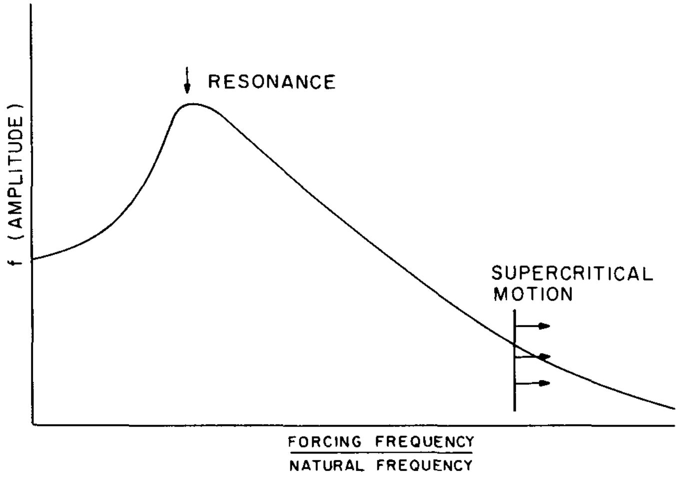

Fig. 16. The supercritical region of motion, showing the region of operation under conditions of favorable pitch characteristics

The longitudinal moment of inertia of the water plane was made small; this, combined with maximizing the longitudinal mass moment of inertia of the hull by moving heavy weights toward the ends and the added mass due to the water entrained by the nacelles, tended to produce a long pitching period.

The early models tested of this concept were largely exploratory and investigated the locations of nacelles, etc. Model tests showed excellent pitch characteristics for the configuration then under study. The short-dashed line in Fig. 17 shows the very favorable behavior in pitch. This figure shows the pitch response in regular waves and is similar to the previous figure except that the forcing frequency or period of encounter is represented as a function of speed. In this instance the wave corresponds to the maximum energy wave in a Neuman spectrum for a state 5 sea.

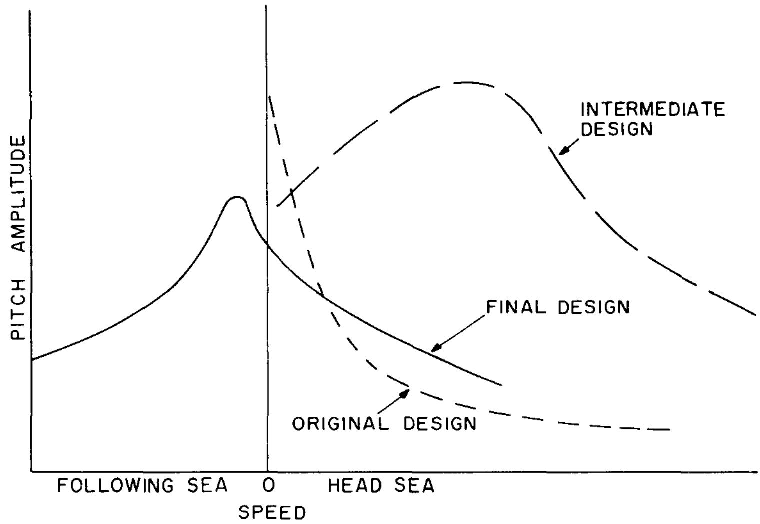

Fig. 17. Pitch behavior of various designs of the escort research ship

When firm requirements were established for the design and the design adjusted to accommodate them it was found that by designing in the new features we had also designed out the favorable pitch characteristics of the original design. The long-dashed line in Fig. 17 shows the disappointing results. The pitch period had been shortened so that resonant pitching occurred near operating speeds.

It was found that we could calculate the period of pitch, using simple single degree of freedom relationships, to agree quite well with model tests by using F. M. Lewis' data for added mass plus allowances based on simplified shapes for the end nacelles. This proved to be a useful design tool and we set about to make changes to lengthen the natural period to approach that of the original design. A period length $T/\sqrt{L}$ was chosen in accordance with Mandel's analysis which would place the design in the supercritical range for all but very low speeds.

This was accomplished by shortening and deepening the hull, shaving away the ends of the water plane to reduce longitudinal moment of inertia, and increasing the nacelle sizes. For a single degree of freedom system the natural frequency is given by

$$f = 2\pi\sqrt{\frac{KI_{wp}}{g(I_s + I_{am})}}$$

where f is the natural frequency in pitch, I_{wp} is the moment of inertia of water plane, I_s is the mass moment of inertia of ship, and I_{am} is the mass moment of inertia of entrained water. The changes enumerated above obviously tend to lower the natural frequency.

It is not easy to alter the natural frequency of a ship while still keeping other characteristics unimpaired. For one thing the longitudinal radius of gyration in ordinary ships is about $0.22L$ or $0.25L$, not counting entrained water. In this design a value of close to

0.30L was needed. It is most difficult to relocate weights in a practical ship design to accomplish this.

By enlarging the end nacelles well beyond the size required for items of equipment, the entrained water was increased and this had the most pronounced effect in increasing the length of the pitching period.

The changes did result in moving the resonant speed back to about zero and the final design exhibited nearly as good pitch characteristics as the original, as the solid line in Fig. 17 shows.

Fig. 18 compares the escort research ship with a destroyer and a destroyer escort. This is a spectral presentation and compares the ships in the same seaway, and at the same speed. The results appear dramatic and in a sense they are, although it should be remembered that the ordinate is a function of pitch amplitude squared, which in effect exaggerates the difference in performance as regards pitch amplitude.

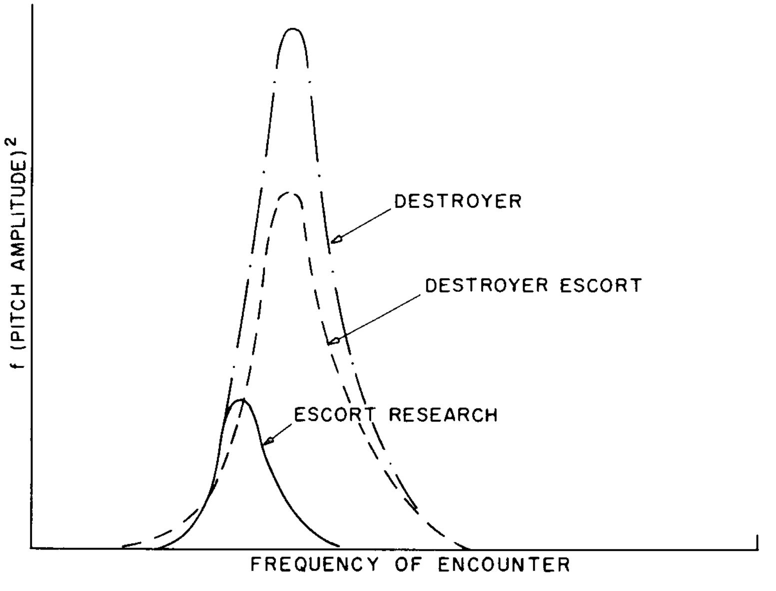

Fig. 18. Predicted pitch spectra in a state 5 sea at a ship speed of 20 knots

The problems and compromises which practical considerations impose on an ideal concept are well exemplified in our experience in this design. One facet, however, did not develop unfavorably. The speed-power relationships provided a pleasant surprise. Fig. 19 shows a qualitative comparison with a destroyer escort hull of about the same displacement. As in the case of the submarine vs destroyer comparison given previously (see Fig. 4) a significant part of the difference in power is the result of the superior propulsive coefficient of the escort research ship. Nevertheless, considering the fact that roughly a third of the displacement of the research ship resides in the nacelles it is remarkable that they cost so little in power.

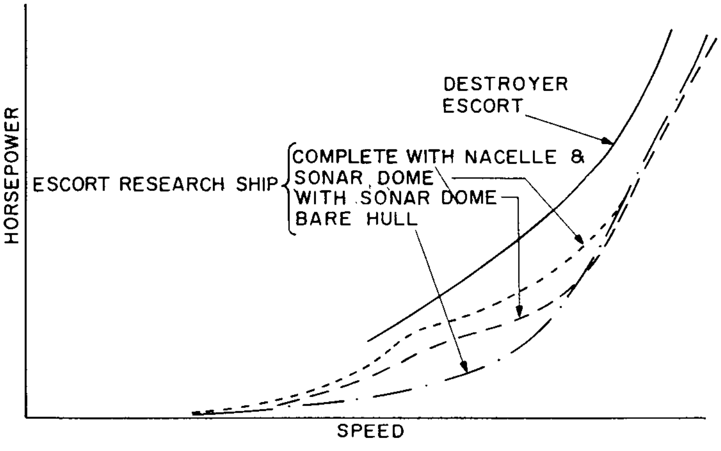

Fig. 19. Speed-power curves for an escort research ship and a destroyer escort of about the same displacement

Some Other High-Performance Ships

Spar Ship—This craft was designed to be an effective and inexpensive sonar ship. The principal idea was to submerge the sonar dome as deep as possible on a surface ship. It was also desired to have minimum motions. Speed was not an important parameter. These ideas led to a ship having a vertical distribution of displacement rather than horizontal (see Fig. 20).

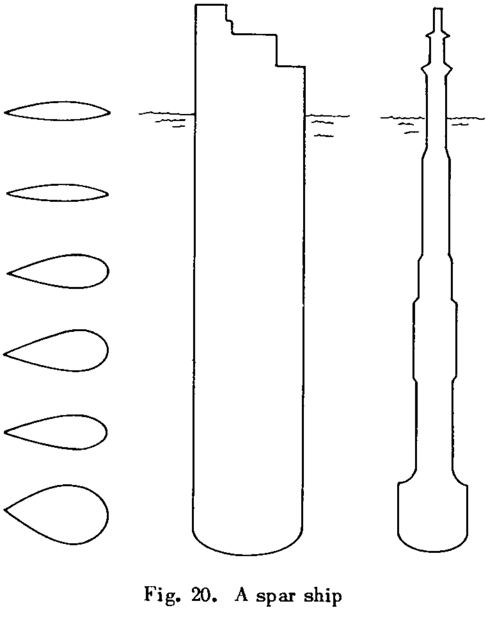

Fig. 20. A spar ship

In the course of exploring the feasibility of this concept a number of interesting problems arose. The speed was low, as expected, but model tests showed that the vertical location of the center of resistance varied considerably with speed. This caused substantial changes in running trim. The form was also highly directionally unstable as one might expect.

Natural heave periods were calculated which indicated supercritical heave motions in practically all seas. No tests were made, however. The practicability of the concept is admittedly questionable. For instance, consider the problem of taking the ship in and out of harbors. The only apparent way to do this would be to provide ballasting arrangements to permit the ship to be brought to a horizontal position. The problems of reorienting through a 90-degree angle are all too obvious and painful, but not impossible.

Catamarans (Planing and Displacement)—The yachting and small boat magazines have had many articles praising the sea-keeping characteristics of planing catamarans. This was all qualitative information. A testing program has been initiated at the David Taylor Model Basin to develop quantitative effects. There are no results at this time. This configuration has promise of allowing planing in relatively high waves, a characteristic that has not been attained with conventional planing craft. Structural problems will require careful attention.

Hulls of Minimum Wave-Making Resistance—Theory by Weinblum, Martin, Kotik and others have developed waterline shapes that should produce minimum wave-making for a given Froude Number. In the speed range of interest, a Coke-bottle form appears to be optimum. As this involves the danger of flow separation, tests are being formulated for comparison of model and theory. Motion tests are planned for the future. If the model tests check the theory, feasibility studies of practical ships will be made to determine application possibilities.

DEVICES TO INCREASE THE PERFORMANCE OF CONVENTIONAL SHIPS

To Increase Speed

In addition to unusual hull forms, there are various devices by which high speeds may be obtained. One such means might be boundary layer control to reduce frictional resistance. This could be accomplished by sucking off the boundary layer at various places along the length of the body. The objective would be to maintain laminar flow; this, ideally, would reduce frictional resistance to about 15 percent of its normal amount. The problem areas are: How much power is needed to suck in the boundary layer? If the boundary layer is drawn off through a porous outer shell, how can clogging of the pores by marine life be prevented? If slots are used, what should their size, shape and location be?

Another possibility is to enclose the body by a gas. Ideally, this would reduce the frictional resistance to about 15 percent of its normal amount. The major problem here is the stability of the gas film. If the gas goes into bubble form, experience has shown that resistance is only slightly decreased.

A third method would be to use a coating that absorbs the energy in perturbations in the water. A theory, as yet unpublished, by Boggs of the United States Rubber Company, indicates that a coating could be devised to maintain laminar flow up to very high Reynolds numbers.

These three methods of reducing frictional resistance may have application to midget submarines, and possibly to larger craft, but theoretical and experimental evidence to substantiate claims and predictions is yet to be acquired. These methods appear to have more promise in a relatively low range of Reynolds numbers than at the high Reynolds numbers at which large ships and submarines operate.

Another approach to the goal of high speed is to increase the efficiency of propulsion devices. No dramatic improvements in this area appear to be in the immediate offing. However, a number of promising new types of propulsive devices are under study and some older ideas are being refined—to name a few: supercavitating or superventilated propellers, pump jets, Kort nozzles, cycloidal propellers, oscillating fins, and two-phase flow jets. Details of these and others, would require too much space for this paper to encompass.

To Control or Minimize Motions

From the control point of view, there are a few devices that hold promise for competing with the highly efficient, standard ship rudder. One of these, the cycloidal propeller, is well known. Another is the jet flap, currently under study for aircraft. Design data, including mass flow vs rudder effectiveness, are being obtained. Yet, another competitor for the rudder is the ring airfoil developed originally for aircraft. Preliminary results indicate excellent control characteristics.

The problem of minimizing motions by using devices has been part of the research effort of the Navy and Merchant Marine for many years. For roll control, gyrostabilizers, active fins, and Frahm tanks are available. Reexamination of the last named, in recent years, has shown that by good design, passive tanks can be quite effective in reducing roll. Considerable effort has recently gone into pitch stabilizers. Fixed fins at the bow can significantly reduce pitch. Under study today are moving fins at bow and stern and flapped ducted propellers.

CONCLUSIONS

High performance ships are basic and very vital objectives of Naval Research and Development. Within the last few years, these objectives have been pursued by special attention to unusual hull forms. A number of these forms are nearing readiness to be incorporated in useful craft; notable among these is the hydrofoil craft.

Modern technical advances, especially in aerodynamics, hydrodynamics, and power plant development are exerting strong influences on ship design. For example, a hydrofoil craft was flown by Alexander Graham Bell at the end of the 19th century, but we would not be investigating, so thoroughly, the promises of hydrofoils if we did not today have high-power, lightweight machinery plants (marine gas turbines), an understanding of supercavitating foils, and strong, lightweight structure.

This is the time to look at our old compromises, and reevaluate them in the light of the new technology. We are not depending on "breakthroughs," but rather recognize that the pace of advance has quickened and the breadth of the front has widened.

The broad spectrum of craft shown in Fig. 21 illustrates the many types of marine craft, and their relative quasi-efficiencies compared to the well-known Gabrielli-Von Karman

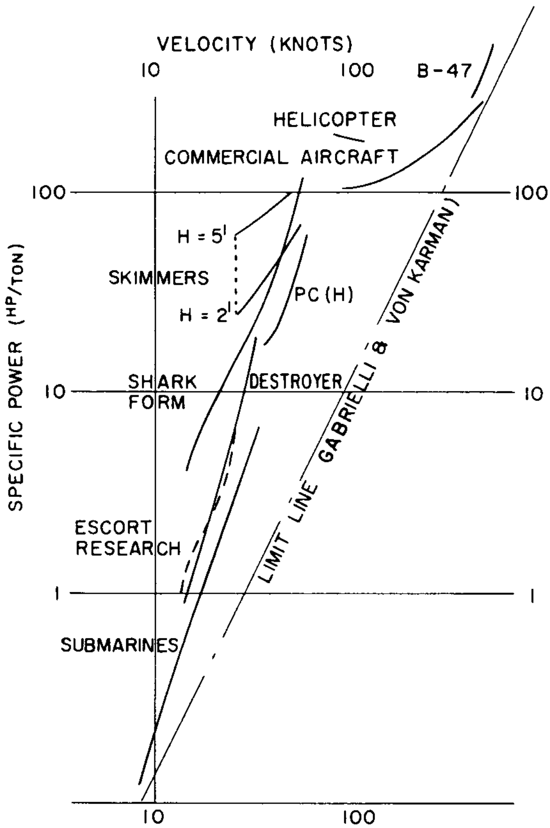

Fig. 21. Specific power curves

limit line. Of course, power per ton is not the only parameter; in the Spar Ship, for instance, this was considered of minor importance. Nevertheless, it does illustrate one facet of our high performance ships.

This paper by no means covers all the possible high performance ships. Only some of high promise have been discussed and these with the caution that for every promise there arises a multitude of problems.

DISCUSSION

(Discussion of this paper is included with that of the following paper, by J. D. van Manen.)

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