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HYDROFOIL DEVELOPMENT -- ISSUES AND ANSWERS

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-- NOTES --

HYDROFOIL DEVELOPMENT--ISSUES AND ANSWERS

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Abstract

Milestones reached in 1974 in the Navy's Hydrofoil Development Program prompt a review of some major design issues and an examination of the degree to which they have been resolved. Issues in three major subsystem areas comprising propulsion, struts and foils, and ship control are addressed. In the area of propulsion, factors relevant to prime movers, transmission, and thrust producers are covered. It is concluded that gas turbine powered mechanical transmissions with supercavitating propellers as thrust producers represent the preferred propulsion system for hydrofoil ships within present technology. In the area of strut/foil design, configurations and materials for construction are covered. It is concluded that fully-submerged retractable foil, canard configured hydrofoil ships are the preferred type for Navy combatants. Ramifications of the unresolved material issue of HY-130 vs. 17-4PH steels are discussed and note is made of plans to resolve the issue. In the area of control, such considerations as flap vs. incidence control of foils, platforming vs. contouring operation, and design features of present analog autopilot control systems are examined. The likelihood of future utilization of a Hydrofoil Universal Digital Autopilot (HUDAP) is noted. In conclusion, it is stated that the technical feasibility and practicality of hydrofoil ships of between 1000 and 2000 tons is no longer at issue and the introduction of ocean-going hydrofoil ships into the fleet will become a future reality.

Introduction

Contrary to the situation in many other countries, the development of hydrofoils in the U. S. has been, in the main, directed at military applications, in particular those of the U. S. Navy. The year 1973 marks several milestones of significance to the U. S. Navy's Hydrofoil Development Program. First, it is the 25th anniversary of the beginning of an identifiable U. S. development effort and interest in the potential of naval hydrofoils. Second, it completes a decade of experience with the Navy's first operational hydrofoil, the 120-ton HIGH POINT (PCH-1). Further, and certainly of even greater significance, it marks the beginning of the U. S. Navy/NATO Patrol Hydrofoil Missile (PHM) ship procurement, the first multiple-ship construction program resulting from the many years of development.

In view of these milestones, it seems appropriate, at this time, to examine the degree to which some of the major design issues have been resolved. It is the purpose of this paper to summarize the results of such an assessment with particular reference to the design of so-called subcavitating hydrofoils, i. e., those designed to operate at speeds up to 50 or 60 knots.

For convenience, the issues examined are grouped into three sub-system categories comprising propulsion, struts and foils, and control. Each of these is discussed in some detail in the following sections, recognizing that the categories of issues are by no means discrete and involve many mutual interactions.

Discussion

Propulsion

The propulsion subsystem is comprised of the prime mover, transmission, and thrust producer. With respect to the prime mover, high-speed light-weight diesel engines and gas turbines have been the two candidates. Light-weight in a diesel engine means around 4 to 5 lbs/hp and engines of this specific weight are available only in relatively low powers, e. g., up to around 3-4000 hp. Driven by economics, the light-weight diesel has been used for some commercial hydrofoil applications but it was never a serious candidate for U. S. Navy hydrofoils even in sizes somewhat less than 100 tons. The marinized gas turbine engine, with its low specific weight (about 1/2 #/hp), low specific volume (.05 to .06 cu.ft/hp), reliability, and availability in sizes up to 25 or 30,000 hp, clearly has been a major factor in the development of Navy hydrofoil ships. This has been enhanced by the more recent trend toward specific fuel consumption in the neighborhood of 0.40 #/hp hr, which is quite competitive with high-speed light-weight diesel engines. Further, the trend toward marinized gas turbines maintaining good values of specific fuel consumption at significantly lower percentages of full power, has also enhanced their use for hydrofoil ship propulsion. This is illustrated by the fuel consumption characteristics of the General Electric LM 2500 turbine, nominally rated at 25,000 hp, shown in Table 1. Thus it may be said that, for U. S. Navy hydrofoils, the use of marinized gas turbine engines has never really been an issue. What is needed, however, is a wider range of available engine sizes (i. e., power) to permit greater flexibility of design choice. For example, at present there is a serious gap in the 6-20,000 hp range, the 15,000 hp LM-1500 currently installed in the 320-ton hydrofoil PLAINVIEW (AGEH-1), Figure 1, being no longer in production. This made necessary the selection of an LM-2500 engine for the PHM even though only 16-18,000 hp is required. On the other hand,

TABLE 1

Specific Fuel Consumption G.E. LM-2500 Gas Turbine*
(59^oF - sea level)

Power/HP	% Max.Cont.HP	SFC/$\frac{\#}{\text{HP-HR}}$	% Min. SFC
23800	100	.39	100
22000	93	.39	100
20000	84	.40	102
18000	76	.41	105
14000	59	.44	112
10000	42	.49	126
6000	25	.58	149

* from Specification MID-S-2500-3 Sep 1972

operation of the engine at considerably lower than full power ratings should result in significantly increased engine operating time between overhauls with only a small sacrifice in specific fuel consumption.

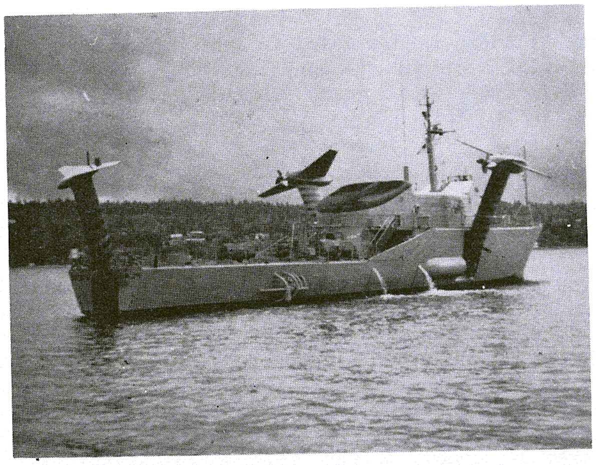

Figure 1. USS PLAINVIEW (AGEH-1)

The central issue with respect to the propulsion subsystem is that of waterjet vs. propellers as thrust producers. This also includes consideration of the transmission since the primary question is one of reliability. The waterjet pump offers simplicity and a small number of moving parts which is considered by many to mean superior reliability when compared to a gear-drive propeller system. Certainly, some of the experience with the four Navy hydrofoils tends to bear this out. In the case of the HIGH POINT, which operated some 719 hours foilborne in its Mod-0 configuration, propulsion system difficulties were experienced in three areas. First, there were problems with the disconnect couplings necessary for the use of the "wet" retraction system, in some cases leading to complete coupling failure. This was ultimately corrected by a re-design which essentially distributed any misalignment over a wider span. Second, there was a continuing problem of salt water entry into the lube oil through leaks in the pod and propeller shaft seals. This was aggravated by the fact that the pods themselves provide the only watertight housing for the lower bevel gear assembly. This problem was brought under control essentially by providing a separate pressurized seal oil system, thereby preventing water entry through the shaft seals. The third area of difficulty was in the tandem propellers themselves. The original three-bladed design of manganese bronze propellers proved very susceptable to cavitation damage as shown in Figure 2 after only a few hours of operation at foilborne speeds. There ensued a series of re-designs of five-bladed versions of various materials including cast 6Al-4V titanium, stainless steel, and nickel-aluminum-bronze (NIBRAL). Marginally acceptable life of several hundred hours was ultimately achieved. The relatively short life was made more acceptable by the development of a technique for replacement underwater with little difficulty. It was the conclusion that the adverse effects of pod-foil-strut wake made design of a non-cavitating 45-knot propeller extremely difficult, if not impossible. The problem was further aggravated by the lack of good tolerance control in propeller manufacture. The overall situation is expected to be further improved in the Mod-1 HIGH POINT configuration change recently completed. As shown in Figure 3, the pods are no longer structural members, having been lowered on short struts below the main foil. This should improve inflow conditions to the aft propeller and delay cavitation as a result of the higher pressure field. Further, the aft propeller has been again re-designed as a partial super-cavitating configuration, which is expected to minimize erosion damage. Provision is also made for the introduction of air to the blades as another possible technique for eliminating or reducing cavitation damage.

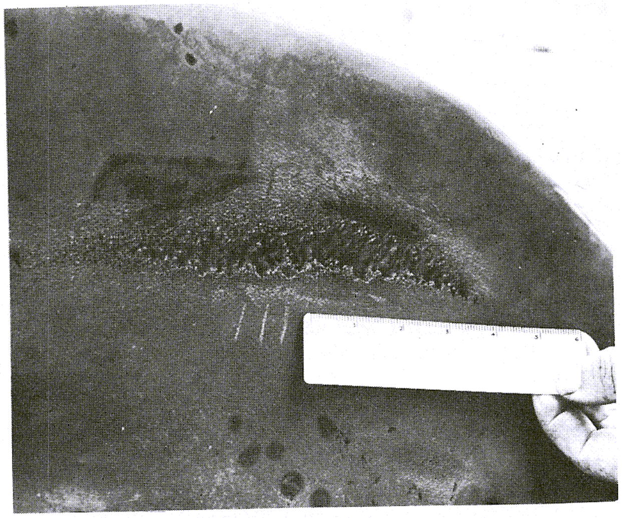

Figure 2. HIGH POINT Mod-0 Aft Propeller Cavitation Damage

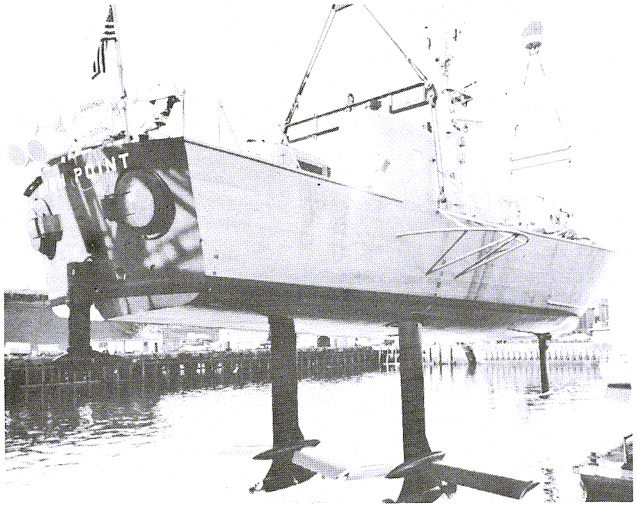

Figure 3. USS HIGH POINT (PCH-1) Mod-1 Strut/Foil Configuration

The PLAINVIEW has the propulsion system shown in Figures 4, 5, and 6. Each of two LM-1500 gas turbines drives a 52-inch-diameter four-bladed titanium propeller of supercavitating design, through right angle bevel gears in separate watertight housings within each pod. This, at the time of its design, represented a significant step forward in the state-of-the-art in size and power of such transmission systems. Experience with this propulsion system in some 195 hours of foilborne operation at speeds up to 50 knots has been quite favorable. No serious problems have developed with the transmission and the propellers are in "like-new" condition with no evidence of cavitation erosion damage.

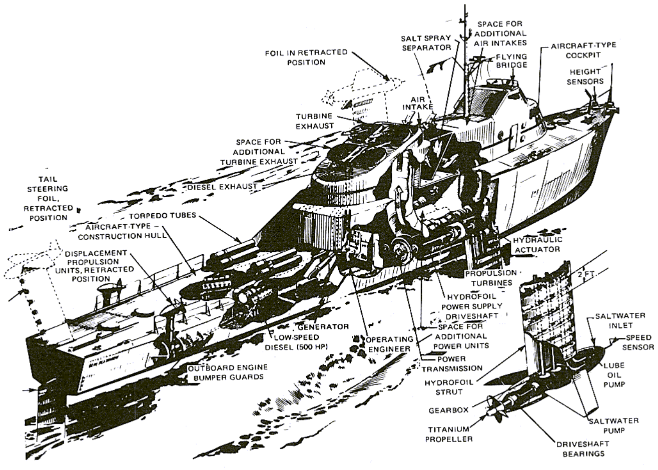

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Figure 4. PLAINVIEW Cut-Away View (Popular Mechanics, Dec 1968)

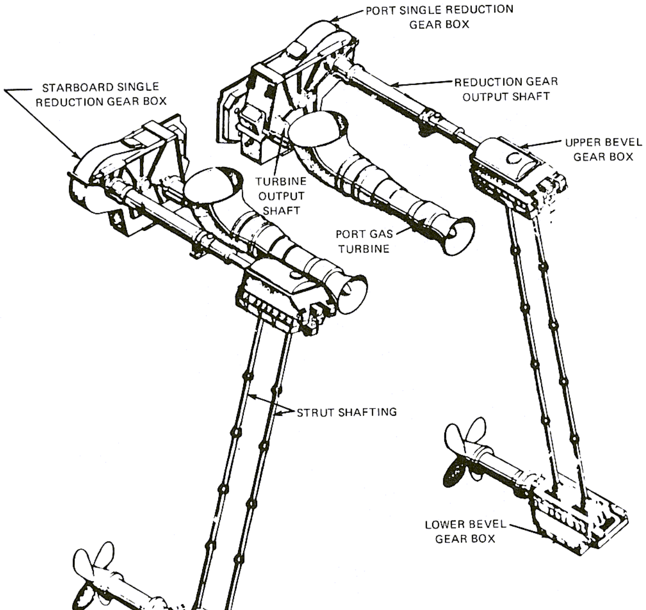


Figure 5. PLAINVIEW Power Train

The 67-ton FLAGSTAFF (PGH-1), shown in Figure 7, is also powered by a right-angle drive propeller system. The KAMEWA propellers have three bolted blades of stainless steel and are of supercavitating design with variable pitch. The requirement for variable pitch results mainly from the use of the 3500 hp Rolls-Royce Tyne engine which did not have a free power turbine. Early experience with the FLAGSTAFF transmission was very poor. Considerable difficulty was experienced particularly with the strut vertical shaft bearings in both the upper and lower gear boxes. These overheated and failed, sometimes in a matter of a few hours. The problem was finally traced to a build-up of tolerances in the vertical strut drive shaft which, as it expanded in heating up during operation, applied excessive loads to the bearings. This problem, attributable to poor design, was corrected completely in a recent re-design and modification made during overhaul, and the transmission has been trouble free in several hundred hours of foilborne operation.

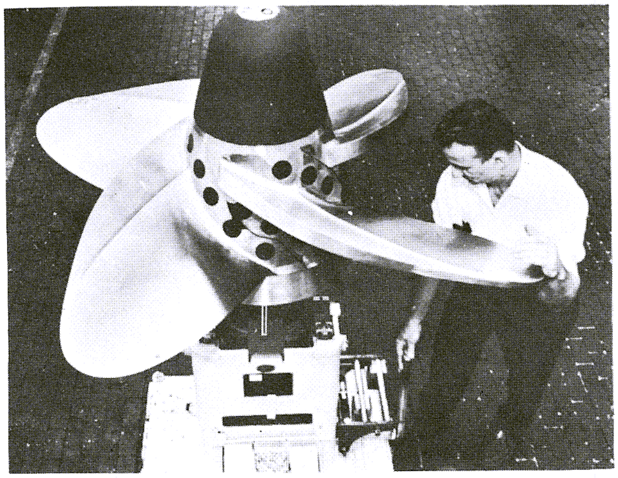


Figure 6. PLAINVIEW Titanium Propeller

The 57-ton TUCUMCARI (PGH-2), Figure 8, was the Navy's first water-jet propelled hydrofoil. Powered by a 3300 hp Proteus gas turbine, thrust was produced by twin nozzles under the transom fed by a double-suction, double rotor centrifugal pump as shown in Figure 9. At design speed of 48 knots the pump produced 25,000 gpm. With respect to reliability, experience with the PGH-2 propulsion system was very good. During almost 1200 hours of foilborne operation there was no evidence of any erosion damage to the pump impeller and the only difficulty experienced in any respect was the development of some cracks in the 4-foot-diameter aluminum pump housing. These were readily weld-repaired in place. The main disadvantage of the TUCUMCARI propulsion system was its low overall propulsive efficiency. At design speed, the overall propulsive efficiency was about 48%. Furthermore, it dropped to 33-35% at take-off speeds of 22 to 24 knots. TUCUMCARI's sad demise is shown in Figure 10. Here she is resting on a coral reef off the coast of Vieques Island near Puerto Rico. The grounding occurred during night exercises with the fleet in November 1972. The craft was subsequently dismantled and the struts and foils and hull have been transported to the Naval Ship R & D Center's Annapolis Laboratory for conduct of various tests. Despite this untimely end TUCUMCARI was a very successful craft. Its many demonstrations of outstanding performance, including an extensive deployment to Europe, undoubtedly did much to precipitate the NATO PHM decision.

Based on the TUCUMCARI operating experience and the desire for high reliability, a waterjet system was selected for the NATO-PHM hydrofoil. The first two of these 235-ton hydrofoils are presently under construction at Boeing in Seattle.

The pump, providing 100,000 gpm at cruise speed of around 50 knots, was designed and constructed by Aerojet-General and is being tested at a land-based test site.

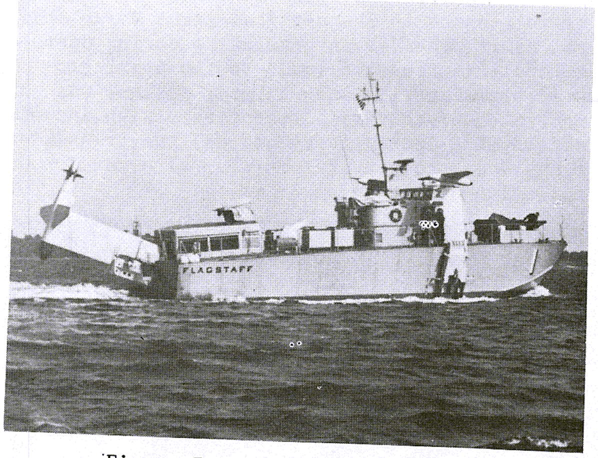


Figure 7a. USS FLAGSTAFF (PGH-1)

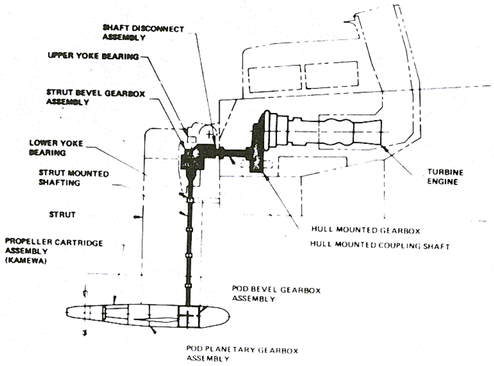


Figure 7b. FLAGSTAFF Power Train

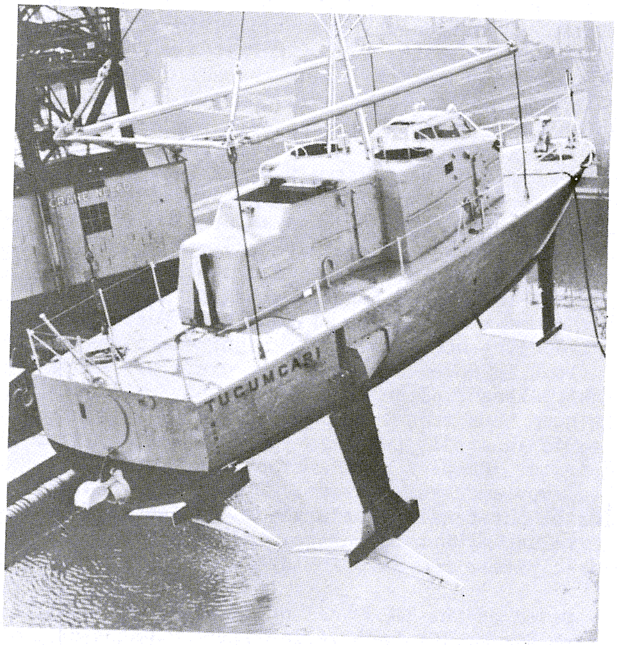


Figure 8. USS TUCUMCARI (PGH-2)

There is no doubt that the low propulsive efficiency of the waterjet represents a severe performance penalty. Furthermore, taking account of the weight of the water in the system, the waterjet in larger hydrofoil ships suffers a significant weight penalty compared to a propeller system. A comparison of efficiencies for a typical hydrofoil is shown in Figure 11. In a design study carried out by Grumman it was found that for a 50-knot hydrofoil of about 200 tons full load displacement, the waterjet provided a weapons payload of 24 tons compared to 47 tons with propeller propulsion. If this additional payload were converted into fuel, it would add about 600 nautical miles to the foilborne range. In another recent study[1], sponsored by the Naval Ship Engineering Center, Hydronautics examined the trade-offs between waterjet and supercavitating propeller propulsion for a nominal 45-knot 750-ton hydrofoil ship. The study concluded that the waterjet is not competitive with a well-designed supercavitating propeller system because the military payload for the selected 2000 nm range would be at best 30-40 percent of that of a propeller system. Further, it was concluded by NAVSEC that the technology is available to design and build a reliable gear system to transmit 25,000 hp to each of two supercavitating pusher propellers required for a 45-50 knot 750-ton hydrofoil ship. The most likely candidate for the pod-mounted reduction gear is the 40,000 hp planetary gear designed and constructed for the Navy by Curtiss-Wright for large hydrofoils and surface effect ships. This unit has been tested on the test stand at power levels up to 50,000 shp.

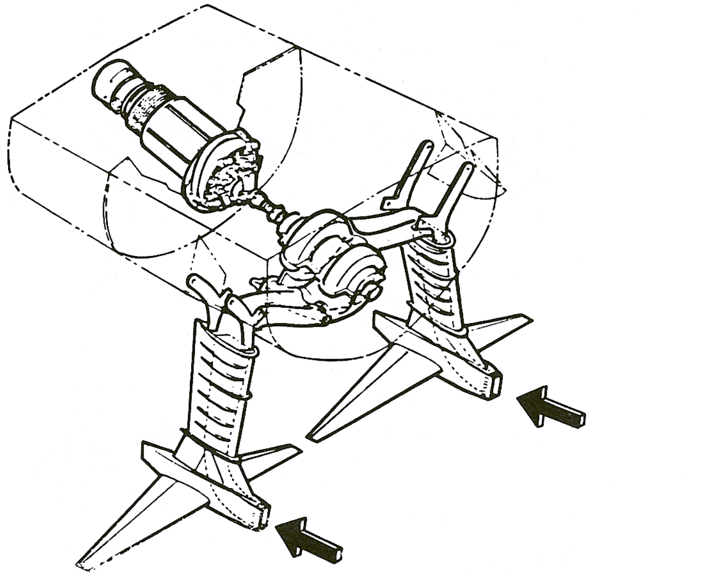


Figure 9. TUCUMCARI Waterjet Propulsion System

In summary, it is the conclusion of the author that the severe performance penalties associated with the use of waterjets for foilborne propulsion of hydrofoil ships makes them a less desirable alternative compared to water propellers. It is also noted that it does not appear feasible to improve the overall propulsive efficiency of the waterjet at design cruise speeds of 45-50 knots by more than a few percent. Even this will be at some sacrifice in greater complexity of the inlet and inlet ducting. Finally, it should be emphasized that past problems of right-angle transmissions for hydrofoils are believed to be solely due to correctable design deficiencies in first-of-a-kind, one-of-a-kind hardware. If one does not seek to save every possible pound in weight, adopts a conservative design approach, and most important, performs adequate life testing of the actual hardware, then there is no reason why reliable gear drive systems for hydrofoil ships of nominal 1000-ton size cannot be designed and constructed within current technology and fabrication capabilities.

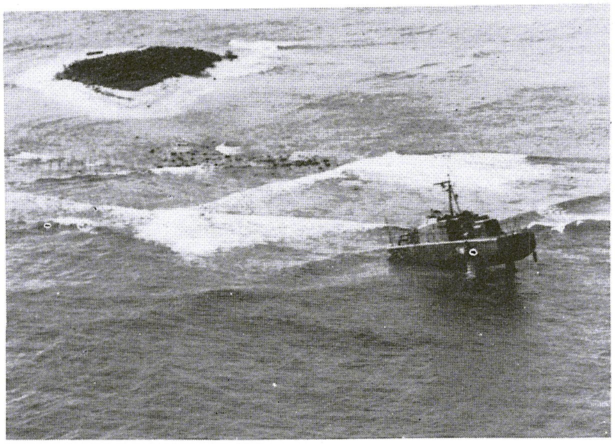


Figure 10. TUCUMCARI Grounding

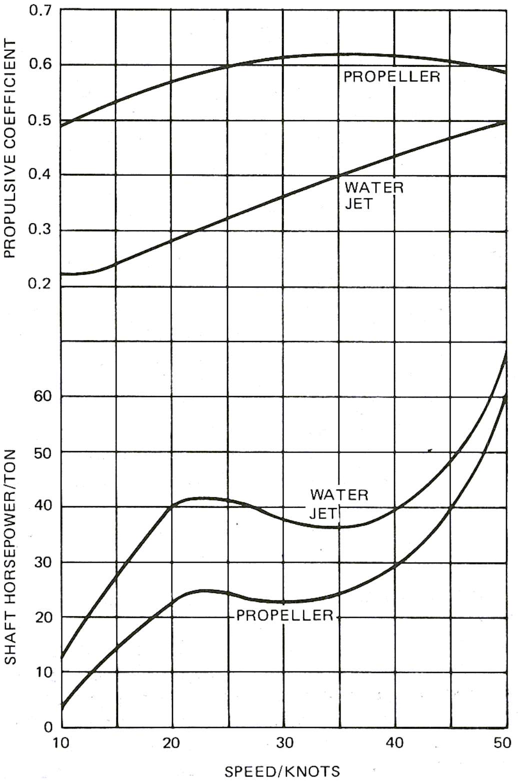


Figure 11. Comparison of Waterjets and Propellers for Foilborne Propulsion of a Typical Hydrofoil

Struts and Foils

There are a number of design issues involved in the choice of strut/foil configuration. One of the earliest of these was the issue of surface-piercing vs. fully-submerged foils. In the surface-piercing system a portion of the lifting surface penetrates the air-water interface thus providing "area" stabilization. In other words, the deeper the penetration of the foil the more lifting surface is immersed and the greater the lift. This results in the attainment of an equilibrium flying height at a given speed of advance. In the fully-submerged system the foils are supported on non-lifting struts which penetrate the air-water interface. The lifting surfaces are, thus, less subject to surface disturbances in rough water and provide a smoother ride in a seaway. Since this system does not provide inherent stability, provision must be made for some form of control. Some of the issues of control design will be discussed in a later section. It may be noted here, however, that, in addition to the superior ride quality, a fully-controlled submerged-foil system also provides excellent maneuverability characteristics which are particularly desirable in a combatant ship.

The 80-ton S. S. DENISON, Figure 12, a joint venture of the Maritime Administration and industry, built by Grumman in 1960, represents a combination of surface-piercing main foils with controllable flaps and a fully-submerged controllable smaller aft foil. Other such hybrids have been widely employed in foreign commercial practice, as for example, the Supramar PT-150. The largest and most advanced surface-piercing hydrofoil ship is the 200-ton Canadian Bras d'Or (FHE-400)[2] shown in Figures 13 and 14. The Canadian choice is understood to have been based not only on arguments of simplicity but on the envisaged operational employment which anticipated hullborne operation more than half the at-sea time. It should be further noted that in the Bras d'Or fixed foil configuration more than one-half the total lift is provided by the fully-submerged center-span of the main foil. Control of the "rake" angle of the bow foil and controllable anhedral tips on the main foils were also provided.

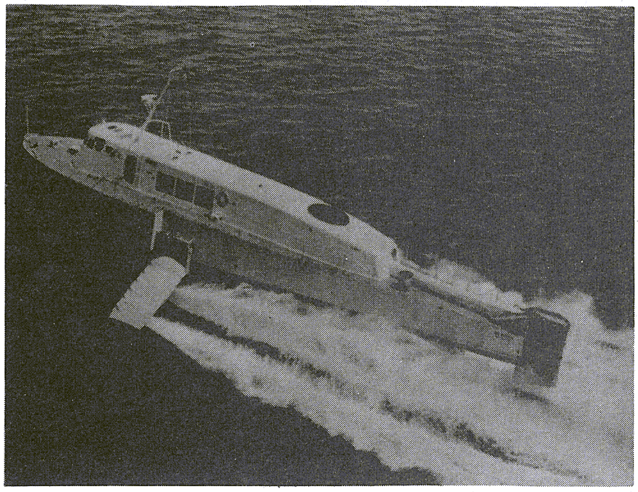


Figure 12. S.S. DENISON

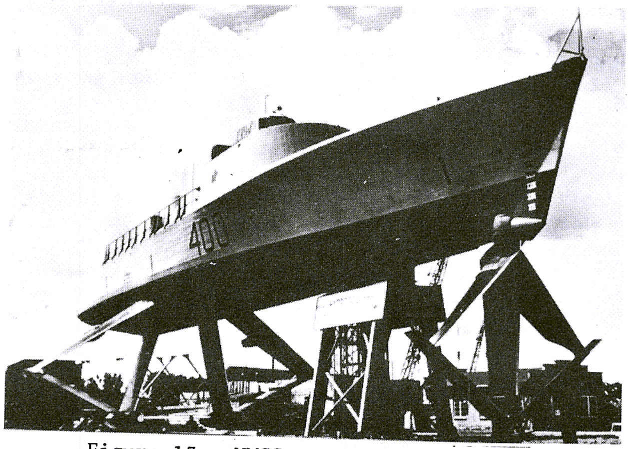


Figure 13. HMCS Bras d'Or (FHE-400) During Construction

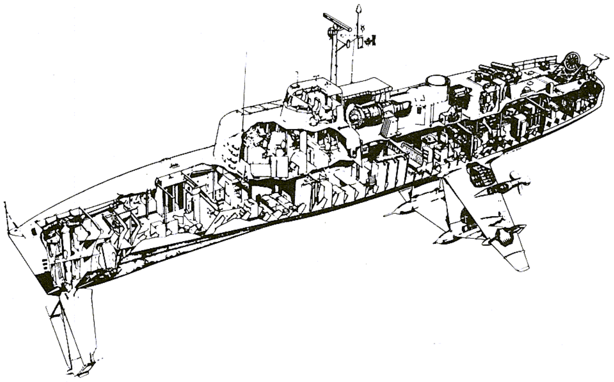


Figure 14. Bras d'Or Cut-Away View

The superior rough water performance and handling qualities offered by the fully-controlled submerged-foil ship led the U. S. Navy to select this configuration in the four operational hydrofoils previously illustrated as well as in the PHM currently being procured. One might, therefore, consider this issue to have been decided some time ago. However, it periodically surfaces under the stimulation of a general dissatisfaction with the lack of valid "hard" data upon which meaningful comparisons of the ride quality of different configurations may be based. The making of such comparisons presents a very complex problem. First, there is yet to be developed a fully satisfactory criterion for judging the ride quality. This is illustrated by the variety of approaches discussed during a symposium[3] on the subject held at NASA's Langley Research Center in July 1972. It seems clear that the magnitude of accelerations experienced in the various degrees of freedom is not alone a sufficient measure. Certainly, at the least, the frequency spectrum is significant. Motions at frequencies of 0.1-0.8 Hz tend to cause motion sickness, whereas, motions in the range of 4-8 Hz cause eyeballs to jiggle and the human viscera to oscillate at or near its natural frequency with potentially disastrous consequences. Such considerations along with other qualitative and quantitative assessments of human responses to motions have led to criteria such as that shown in Figure 15.

Hydrofoil motions in the foilborne mode of operation tend to fall in the areas indicated and are in a range of frequencies lower than those covered by the ISO standard.[4] Here, also, there are serious questions stemming from the fact that "all things are not equal" in the data that are being compared.

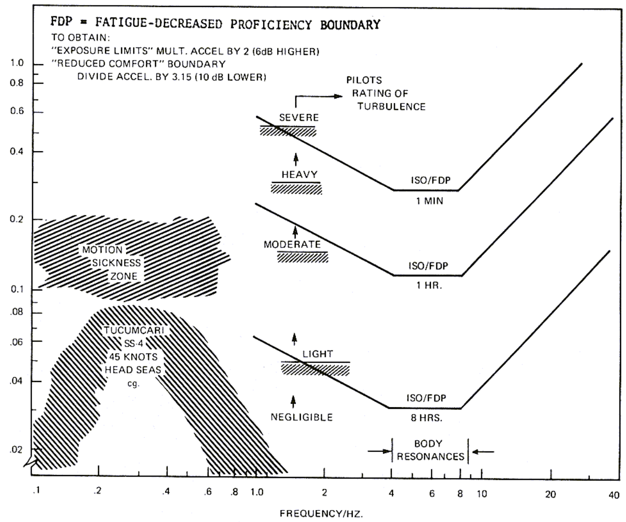


Figure 15. Ride Quality Criteria

For example, lateral accelerations are also of considerable significance in overall ride quality. Levels of lateral acceleration only 1/2 of objectionable levels of vertical acceleration can produce adverse response. This results, primarily, from the considerably larger moment arm represented by the distance from the deck to the cg of a standing human. Here, it might be noted that surface-piercing foil craft tend to exhibit higher levels of lateral accelerations than comparable submerged-foil craft and this is felt to be a significant factor in relative ride quality.

Another consideration in assessing ride quality of military vehicles is the factor of experience of operational personnel. It is well recognized that psychological factors play an important role in human response to motions. An individual who would be totally undisturbed by rather extreme acceleration levels experienced in daily travels on a commuter train, might well react adversely when experiencing, for the first time, significantly lower levels of acceleration on a hydrofoil craft. Just the apprehension generated by lack of familiarity and confidence in the vehicle's safety can be a significant factor in human response.

Another problem lies in the very real difficulty of properly characterizing the seaway. By virtue of their use of a wave-height sensor as part of the control system, fully-submerged foil craft have provided extensive data on wave amplitudes correlated with craft motions. Actual wave heights encountered along a track are obtained by correcting the height sensor output for the motion of the craft. Some wave direction information can be obtained by making comparisons of wave encounter frequency records of runs in different directions. It is recognized, however, that this still does not provide a true representation of the actual energy spectrum of the waves. In the final analysis truly valid comparisons of ride quality can be obtained only through side-by-side trials using essentially duplicate instrumentation systems. It is indeed unfortunate that even qualitatively there have been few, if any, such comparisons between surface-piercing and fully-submerged foil craft. In fact, for all practical purposes, the same deficiency applies to comparisons of hydrofoil ships with displacement ships and other advanced craft.

In spite of this rather sad state of our ability to resolve this issue in a manner completely satisfying to the designer, there has been collected a large body of data on the motion characteristics of various hydrofoil craft operating in various sea conditions. These data have been augmented liberally with the sensory impressions recorded by many who have ridden on and compared the ride quality of different craft. It is felt to be widely conceded that such appraisals definitely do verify the superior rough water performance and maneuverability of the automatically-controlled fully-submerged foil ship. It may also be noted that U. S. Navy experience to date, covering more than 2000 hours of foilborne operation, demonstrates that the electronic autopilot, which is based on proven aircraft technology, is one of the most reliable equipments on the craft. To this author's knowledge there has never been a failure of an electronic autopilot in foilborne operation of any of the four Navy hydrofoils.

A second issue of foil configuration is that of the distribution of foil area in the longitudinal direction. There are basically three different configurations which are more-or-less arbitrarily defined. In the canard arrangement, 65% or more of the lifting area is aft of the center-of-gravity of the ship. In the conventional or airplane arrangement the reverse is true. Finally, a tandem configuration is one where the foil area is essentially equally distributed fore and aft of the cg. Although tandem configurations were looked at early in the development effort, they were never seriously considered for operational hydrofoils but may look attractive for larger ships. In the other two cases, Boeing adopted the canard arrangement and Grumman the airplane arrangement. PCH-1, PGH-2 and PHM thus are representative of the Boeing approach while the AGEH-1 and PGH-1 are representative of the Grumman approach.

One might say this is not really an issue since there is no doubt that either approach can be followed to produce an acceptable design. The primary considerations involve machinery arrangement, mission equipment and utilization, retraction of struts and foils, and dynamic stability and control. The canard arrangement places the machinery well aft in the ship. This offers advantages in turbine inlet duct design and is particularly attractive in permitting engine exhaust astern. It also avoids the necessity for an access passageway through the machinery space and places normally occupied spaces well forward. This enhances habitability. If waterjet propulsion is used, a canard arrangement is almost mandatory if an acceptable machinery arrangement is to be achieved.

There are a number of considerations relating to mission equipment. For example, for the purposes of towing, as in the case of variable-depth-sonar, the canard arrangement with the major lifting surface area aft is more desirable. In the case of a deck gun installation extending below the main deck, a bow gun location would call for conventional whereas a stern gun location might dictate a canard arrangement.

From the standpoint of retraction either approach is acceptable. A canard arrangement with a single strut forward can become somewhat messy in that it generally necessitates some type of bow door arrangement. This was the case with TUCUMCARI and is also the approach adopted for PHM. This is not, however, considered to be a driving consideration.

Finally, from the standpoint of stability and control, it is conceded that acceptable characteristics can be achieved with either configuration. Nevertheless, it is felt that the canard arrangement offers some significant advantages. In rough water, it is the forward foil that is likely to "broach," i. e., occasionally penetrate the air-water interface in going through a wave trough. In the broaching of a split forward airplane configuration there tends to be an unbalance between the port and starboard sides. This introduces a roll moment not exhibited in the symmetrical canard case. Further, in the canard case, the larger lateral strut area is aft and this is felt to offer less likelihood of strut unwetting in rough water with attendant loss of lateral stability. The airplane configuration also produces a large bow overhang. Although not yet demonstrated by experience, this is felt by some to be undesirable in view of the possibility of large asymmetric loads from wave impact in high speed turns in rough water.

In light of these considerations, it seems clear that, even though either configuration is acceptable, the canard arrangement is generally preferred and the tandem configuration has not been adequately explored in the craft sizes built to date.

A third issue pertinent to the strut/foil subsystem is that of material selection. The search for a completely suitable material of which to construct the struts and foils has been one of the leading frustrations of the Navy development program. To find such properties as high strength, resistance to corrosion and cavitation erosion, good fatigue characteristics, repairability in the field, all embodied in one material, has offered a real challenge which, thus far, has not been met with complete satisfaction.

There are a number of metal alloys which have been seriously considered for strut and foil construction. The PGH-1 foils are made of solid forged 6061 aluminum coated with Laminar X500 Urethane. They have proved entirely satisfactory in more than 600 hours of foilborne operation and require relatively little periodic touch-up of the coatings. Unfortunately, however, the use of aluminum rather rapidly becomes impractical with increase in foil size. The relatively low strength results in unacceptable penalties in foil thicknesses and weight.

The corrosion and cavitation erosion resistance of Inconel 718, a precipitation-hardened nickel base alloy led to its consideration as a candidate material. The DENISON supercavitating propeller was made of this material and proved quite satisfactory. Again, however, a number of serious disadvantages essentially ruled it out for strut/foil construction. Also, it is relatively difficult to machine, requires a complex and lengthy heat treatment, and its use is costly.

A third material which both excites and frustrates the designer is titanium. Specifically 6Al-4V-Ti in earlier considerations and, more recently, 6Al-2Cb-1Ta titanium with .8 molybdenum offers excellent resistance to sea water corrosion and damage due to cavitation erosion. It has a high strength-to-weight ratio and is obtainable in plate with guaranteed 100,000 psi yield strength. Again however, there is one real and one possible fly in the ointment. The real problem is in the welding of built-up strut and foil sections. Titanium welding requires the use of inert gas to protect it from atmospheric contamination which causes embrittlement. In strut/foil weldments the blind side of the welds is not accessible and, as yet, no proven technique has been developed to circumvent this problem. Another possible problem may result from the low elastic modulus of titanium compared to that of steel. This raises some potentially serious questions regarding deflections and hydroelastic instability of struts constructed of titanium. Regardless of these considerations, the many attractive features of this material continue to stimulate investigations of means to make its use feasible including such techniques as cladding of other more fabricable materials with a titanium outer cover.

Elimination of the three preceding materials from consideration for current strut/foil construction, such as that of PHM, leaves only two types of materials as candidates. These are the HY high yield low carbon steels, e. g. HY-80, HY-100, HY-130, developed by the Navy for submarine construction, and the precipitation-hardening corrosion-resistant steels, e. g., 15-5PH and 17-4PH.

HY-80 was used in the construction of the original PCH-1 struts and foils, some of which has been replaced by HY-130 in the Mod-1 configuration. The AGEH-1 struts and foils are constructed of a combination of HY-80 and HY-100. The TUCUMCARI struts and foils were constructed of 17-4PH except in a few parts where considerably lower strength type 304 stainless was inadvertently introduced. The TUCUMCARI foils are solid 17-4PH forgings.

The High Yield steels are tough and readily weldable; however, they are not resistant to sea water corrosion and must therefore be coated. HY-130 may have a lower corrosion fatigue limit but this has not yet been fully verified. This might present a problem if it were not possible either to make the struts and foils watertight or coat the internal surfaces to prevent contact with sea water in the event of leakage.

The precipitation-hardened steels exhibit good corrosion and cavitation erosion resistance and have yield strengths equivalent to HY-130, e. g., 130,000 psi. Their main disadvantages are the need for post weld heat treat (whereby they are not field repairable), their lower toughness compared to the HY steels, and potential problems with stress corrosion cracking. 17-4PH also exhibits severe crevice corrosion pitting in areas where the water velocities are below 3-4 ft/sec.

Boeing is using 17-4PH as the strut foil material for the two PHM lead ships now under construction. This selection was based on many factors including experience with TUCUMCARI, aircraft experience, the ready availability of these steels in thicknesses and quantities required, and some skepticism regarding the availability of a completely satisfactory coating for HY-130. This decision was not concurred in by many in the Navy technical community. Their contention is that HY-130 is the better alternative. This is based on the conviction that acceptable coatings <u>are</u> available as borne out by successful experience with <u>external</u> coating of FLAGSTAFF and PLAINVIEW struts and foils. Early experience with a number of coatings on HIGH POINT was, on the other hand, very bad. Much of this difficulty was ultimately traced to the poor tolerances in maintaining critical contours, i. e., fairness of struts and foils. This caused severe cavitation in local areas and resulted in rather rapid erosion damage. Once this problem was uncovered, corrective measures were taken which considerably improved coating life. It also must be emphasized that HIGH POINT has a "wet" retraction system. The coatings are, therefore, not accessible for routine maintenance. This will not be the case with PHM which will have full dry retraction. PLAINVIEW's external coatings have proved satisfactory. However, there has been some significant internal corrosion, and the adequacy of watertightness and <u>internal</u> coatings remains questionable.

As a consequence of the several questions that remain unresolved with respect to this issue, it is proposed to design and construct an alternate PHM strut and foil of HY-130. Further, it is planned to replace the present tail strut on PLAINVIEW with one constructed of HY-130. These steps along with current examinations of TUCUMCARI 17-4PH struts and foils and laboratory tests of structural samples of each material should resolve this issue. In any event, it should be understood that neither material presents any critical problem involving short term catastrophic structural failure. Of concern, here, are questions of potential long term degradation of material properties.

Ship Control

Having chosen a fully-submerged foil configuration, one must then address a number of issues relevant to the necessary provision of means to control the ship in its foilborne operation. Figure 16 is a simplified block diagram of the hydrofoil ship control system which basically comprises a computer, sensors and displays, and force producers with their associated actuation components.

Before consideration of some of the more hardware-oriented design issues, it is necessary to address some of the fundamental questions relating to the philosophy of approach to control. For example, there is the issue of flat vs. banked or coordinated turning. Except for TUCUMCARI, provision was made for selection of either mode of turning in the Navy's operational hydrofoils. In the original HIGH POINT configuration, foilborne steering was accomplished by a trailing edge flap on the fixed forward strut and, on the same shaft, a spade rudder beneath the forward foil. In early operations, HIGH POINT suffered considerable difficulty in erratic turning behavior. After an extensive period of investigation, too long and too painful to belabor here, it was determined that the principal difficulty resulted from manufacturing inaccuracies in the contour of the main aft struts. Flat spots of sizable area caused occurrence of cavitation and erratic ventilation which generated large unbalanced side forces and, in turn, caused loss of lateral control and skid-out of the stern. This was corrected by refairing of the struts.

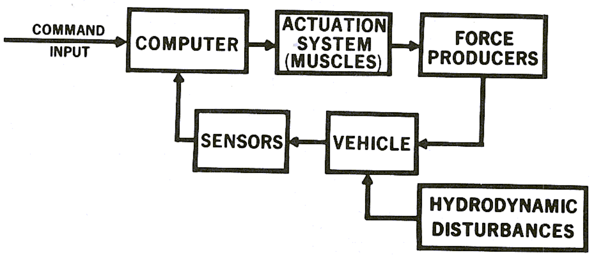
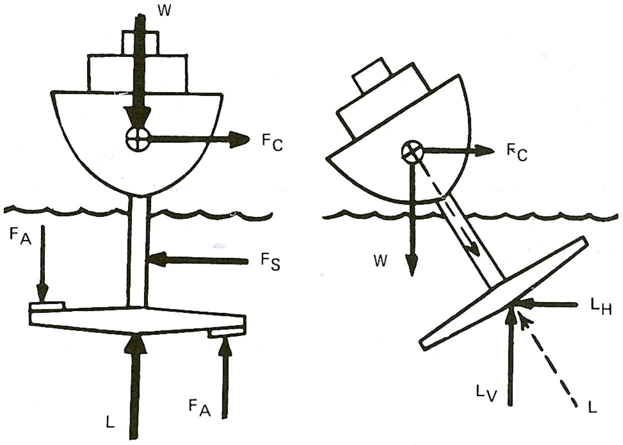


Figure 16. Simplified Block Diagram of Hydrofoil Ship Control

Both FLAGSTAFF and PLAINVIEW are steered by rotation of the aft strut/foil assemblies as rudders. TUCUMCARI had a swivelable forward strut which, in a banked turn, was servo-controlled as a function of roll angle to produce a nulling of strut side forces.

In support of the flat turn mode, it was argued that in banked turns there is the possibility of venting a foil by having a foil tip approach too closely to the air-water interface, particularly in rough water. It was also contended that aiming of a gun would be impaired by the heeling over of the ship in a banked turn. Advocates of the banked turn mode were concerned with the high strut side forces and potential for ventilation of struts in high-speed flat turns. Further, they pointed out that there are benefits in maintaining the human's apparent gravity axis perpendicular to the deck in banked turns. Some of these points are illustrated in the force schematic shown in Figure 17.

The excellent turning characteristics of the TUCUMCARI coupled with experience in operating the other Navy hydrofoils has clearly demonstrated the advantages of a banked-turn mode. The HIGH POINT, in its Mod-1 configuration, now has a swivelable forward strut and banked turning is accomplished entirely by flap control with the forward strut controlled to null the strut side force. This configuration has also been adopted in the PHM design. Similar to the TUCUMCARI, the outboard semi-spans of the main foils of both HIGH POINT and PHM have been given negative dihedral to minimize the risk of tip ventilation in turns, and to assure adequate lateral area for directional stability.



FLAT TURN

CO-ORDINATED TURN

Figure 17. Turning Force Schematic

As is the case of all ships, the seakeeping capability of a hydrofoil ship is related strongly to the length of the ship in comparison to the length of the waves in which it is operating. By use of a control system, however, hydrofoil ships of relatively small size can be given high-speed seakeeping capabilities which considerably exceed those of much larger displacement ships. By suitable design the automatically-controlled hydrofoil ship can be made to follow the contour of many of the waves in which it operates or, conversely, maintain the trajectory of its center-of-gravity along a horizontal path. Clearly, there are limitations to both the contouring and platforming modes of operation. If the waves become very steep and high compared to the size of the ship, then simple geometry rules out complete contouring of the waves. Further, if the length of the struts is relatively short compared to the height of the waves, the pure platforming mode is no longer feasible and foil broaching with attendant hull impact occurs. This led earlier to provision of both a contouring and a platforming mode, available at the option of the operator. Also, it was considered important to establish the normal flying height so as to essentially avoid contact with the waves in all seas up to design sea state. Rough water foilborne trials with HIGH POINT in its original configuration demonstrated the need to modify some of the concepts of foilborne operation. It was found that the platform mode, to the degree possible within limitations of the control and the wave conditions, was preferable. Further, it was determined that flying at lower keel heights produced a smoother ride. This was primarily due to the fact that broaching of the forward foil and resulting bow impacts, characteristic of maximum foilborne flying height, produced much higher vertical accelerations than those generated at lower keel heights by penetration of the hull through the wave crests. This latter type of operation is referred to as "wave-furrowing" or "wave-cresting". Broaching of the forward foil of HIGH POINT, was aggravated by the length of the forward strut, it being two feet shorter than the aft struts in the original configuration. It was subsequently lengthened in the Mod-1 conversion.

In summary, analysis, simulation, and operational experience have demonstrated that optimum ride characteristics result from a proper blend of contouring and platforming and a dominant design consideration is the length of the forward strut in relation to the design maximum wave heights for foilborne operation.

Another issue, closely interrelated with that of contouring vs. platforming operation is the manner of lift control. Here, there are a number of considerations which influence the choice of lift control device. They include hydraulic power requirements, characteristics of foil rewetting after broach, limits of control authority introduced by foil cavitation, lift/drag ratio, and reliability. There are three principal methods of lift control that have been considered in the Navy development program. These are flap-control, incidence control (where the entire foil is moved to vary its angle of attack), and control by injection of air from openings in the foil thereby changing the pressure distribution.

With respect to so-called "air feed" or "air bleed" systems, such as that proposed by Supramar and currently in use on some commercial craft, the Navy is sponsoring experiments by Supramar to establish hydrodynamic characteristics more fully. The primary attractive features of this system are its rapid response and its simplicity thereby offering potential for greater reliability. A disadvantage lies in the relatively high drag penalties which appear to be characteristic of foil sections thus far employed. This may be overcome by development of section shapes particularly suitable for the application; however, such development is felt to require a rather extensive test program. As a result, this means of lift control will not be further addressed herein.

Both other methods of lift control have been employed in the Navy's operational hydrofoils. Again, there has been a different view adopted by Boeing and Grumman. Thus, the HIGH POINT and TUCUMCARI have flap control and PLAINVIEW and FLAGSTAFF have incidence control. In the case of the two PGH's it may be said that both systems are adequate. However, with increase in size of the craft, hydraulic power requirements for incidence control become quite large in comparison to a flap control system. This is illustrated in Figure 18 where requirements for the four Navy craft are compared. These are all 3000 PSI aircraft-type hydraulic systems. Here it should be noted that values on the curve are those that would give 100% redundancy which is not actually the case for some of the craft. All values are, thus, not representative of installed systems.

The original design of PLAINVIEW called for foil rates of 22 degrees per second to be supplied from either of two separate hydraulic power supplies. The foil rate requirement resulted from the goal of accommodating to changes of angle of attack associated with speeds of 50 knots in state 6 sea. The orbital velocities occurring in waves of this sea state are around 8 ft/sec. Thus, at speeds of 50 knots (80 ft/sec.), the change in angle of attack is around ± 6°. Considering that the static plus dynamic forces on an AGEH main foil produce peak hinge moments of around one million foot-pounds, the large hydraulic power requirements are not surprising. 3000 PSI pumps at flow rates of over 200 GPM were required, with total flow rates of about 1000 GPM, including ship service requirements, making it larger than any aircraft hydraulic system.

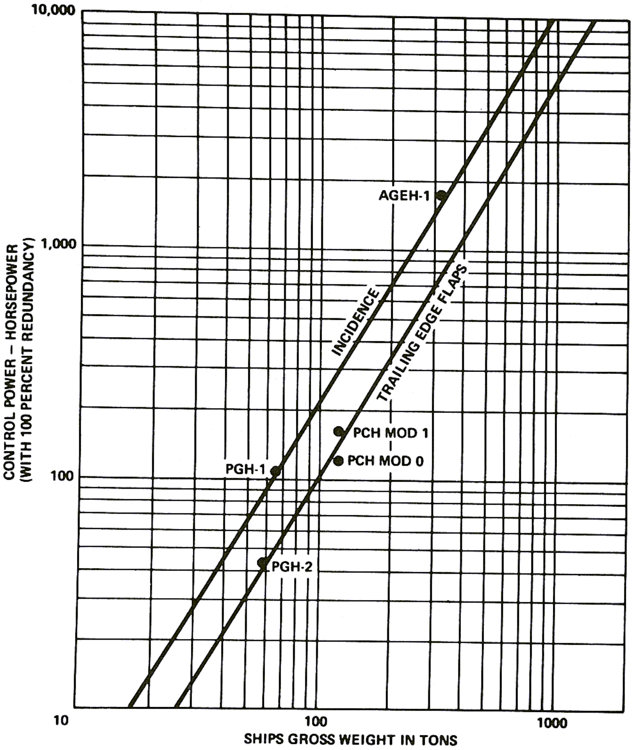


Figure 18. Comparison of Hydraulic Power Requirements for Flap and Incidence Control

Experience with PLAINVIEW in foilborne operation proved to be somewhat of a hydraulic nightmare. The many fittings of the hydraulic tubing running throughout the ship, some of very large diameter, were subject to continual leaks and, at times, the ship became saturated with hydraulic fluid. It was said that, during the worst periods of difficulty there were occasions when hydraulic fluid was used at a rate greater than the fuel rate for hull-borne propulsion. Over a period of time, with great perseverance and effort, mainly by the crew, the hydraulic leak problem was brought under control. It was clear, however, that a more permanent fix involving complete repiping with welded fittings was required. This is being instituted during the current overhaul of the ship.

Foilborne operation of PLAINVIEW in moderately rough water has produced additional information which has led to a change in the design philosophy and which has increased support for the choice of flap control. It has been found that moving the foils up and down in an attempt to maintain an essentially constant angle of attack in waves, is a self-defeating process. The inherent lags in the total system make this a practical impossibility and the phase shifts result in a mis-match that does more harm than good. Actually, it turns out to be far better to ignore the higher frequency transients by reducing control gains to a minimum. Such fluctuations in velocity have little or no effect on the ship due to its large inherent inertia and damping. This experience has led to a re-design of PLAINVIEW's incidence control, under a contract with Grumman, directed towards the idea of a modified flap-control with slow incidence trim by something like a lead-screw arrangement. This is expected to permit employment of the advantages of both approaches without some of the inherent disadvantages of full incidence control.

There is also some evidence that flap-controlled foils re-wet after broaching faster than incidence-controlled foils. This may be due to the fact that the angle of attack of the flap-controlled fixed-incidence foil is determined by the pitch angle of the craft and it cannot be driven to extreme incidence angles by command from an autopilot which is unable to properly recognize the unwetting phenomenon. This is still subject to some question, however, since the flap-controlled Navy craft have canard configurations whereas the incidence-controlled craft have airplane configurations. Furthermore, design foil loading varies considerably, it being 1000-1100 PSF for TUCUMCARI, 1300 PSF for HIGH POINT and 1400-1500 PSF for PLAINVIEW and FLAGSTAFF.

On balance, in light of experience to date, the flap-control system is preferable except, perhaps for small hydrofoil craft. It is also noted that wherever practicable, hydraulic actuators should be located in the ship with connections to the flaps being made by means of mechanical linkages. Keeping the actuators accessible and out of salt water environment is more desirable in enhancing reliability and maintainability of the system.

With respect to the electronics part of the hydrofoil control, an analog approach was adopted in all four of the Navy craft. The output of motion sensors is processed by a control computer and continuous proportional commands are sent to the control surface actuators. With experience in operating craft in rough water and the development of more sophisticated computer simulation tools, the control electronics has become less rather than more sophisticated. This is not too surprising since in the earlier phases of development there were limited data on full-scale motions and the tendency was to incorporate quite a bit of flexibility in varying autopilot control parameters over a wide range. Figure 19 is a diagram of the most advanced analog system which is represented in the present HIGH POINT configuration. This is also essentially the system to be put into the PHM.

Although the analog autopilot is adequate for present applications there has been a growing interest in its replacement with a hydrofoil universal digital autopilot (HUDAP)^{5}. The digital systems offers a number of advantages over the analog approach, not the least of which is the fact that it can be made universally applicable to any fully-submerged hydrofoil ship. It also offers increased reliability and less maintenance, it facilitates crew training and logistic support, and, very importantly, its computer can be used to handle other functions such as navigation and fire control. Basically, the universal controller differs from the present analog system only in the provision of a digital computer to perform all shaping, logic, interconnect, redundancy, and self-monitoring functions. It will have a simple punched-tape program loader which will adapt it to various hydrofoil ships and control philosophies. The system will also include a sensor package comprising sensors for pitch, roll, height, vertical acceleration, yaw, flap positions, rudder position, and additional channels for as yet unassigned inputs; a servo-amplifier package for the control surface actuators; and pilot house command inputs, displays, and self monitoring features. Such a system has been designed and is being procured and will soon be installed as an alternate in HIGH POINT with provision for switching to either system. This demonstration system will provide for self-checks of each circuit ten times each second. If a circuit does not pass a reasonableness check there is provision for automatic switching to a redundant circuit. A selectable automatic heading hold and pre-programmed maneuvers such as Williamson turns are also provided in the demonstration system.

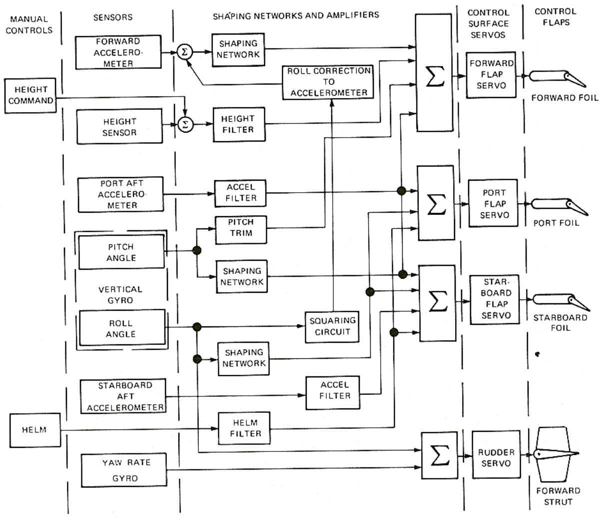


Figure 19. Diagram of HIGH POINT Mod-1 Analog Control System

One final issue which merits some discussion relative to ship control is the height sensor. Until recently the height sensor which has been used is an ultra-sonic type. It is thus susceptible to some forms of extraneous noise such as might be associated with weapon firing or aircraft close overhead. This has led to the investigation of an alternate radar sensor which is essentially the same unit as that used for helicopter hovering control. Both types of sensor are presently installed on HIGH POINT and are undergoing side-by-side evaluation. Early indications are that the radar sensor is definitely superior to the sonic type.

By way of summary it may be said that the design of the hydrofoil automatic control system, based on proven aircraft technology, is well in hand and all major design issues have been resolved. The process now is one of engineering optimization driven by considerations of universality, reliability, maintainability, and least cost.

Conclusions

In the preceding discussion, an attempt has been made to highlight some of the major design issues which have been confronted in the Navy's hydrofoil development program, and assess the state of their resolution. In so-doing, it is recognized that the treatment is by no means comprehensive and all-inclusive nor is it likely to represent the "final" word in view of the continuing evolution of the technology underlying this challenging marine vehicle development. One thing certainly seems to be clear, however, and that is the firm conviction of the technical community that the feasibility, and practicality, of hydrofoil ships of about 1000 to 2000 tons is no longer at issue. Even though continuing development of the underlying technology is needed, the major emphasis has shifted to issues of engineering optimization to maximize producibility, reliability, maintainability, supportability, and to reduce cost without sacrifice in performance. Finally, it is also clear that the full exploitation of this new naval capability requires a detailed assessment and acceptance of the roles and mission applications of hydrofoil ships and craft in the Navy of the future. It was thought that the two gunboats, FLAGSTAFF and TUCUMCARI, would be the first step in this direction. Unfortunately, this did not prove to be the case. This was not because either craft failed to meet its design requirements but because of an admixture of many other factors. Their size proved to be smaller than desirable and their role and mission application was never clearly spelled out and accepted by the operational forces. But, more than anything, it is felt that their lack of acceptance resulted from the failure to recognize the steps needed to establish firmly the requirements and specifications for new systems totally unfamiliar to the forces afloat. It must be accepted that a considerable period of operational experimentation and familiarization is needed to lay the proper foundation for selecting the characteristics desired of a production prototype. It is difficult, if not impossible, to make credible paper assessments of a system offering capabilities totally beyond those heretofore existing. It is necessary to develop entirely new tactics and strategies in order to fully exploit such capabilities. Further, and perhaps of greatest importance, there must be parallel development of weapons and other mission equipment compatible with these new platform characteristics.

The NATO-PHM represents a new initiative toward introduction of hydrofoil ships into the fleet. With the successful demonstration of the two lead ships in operational test and evaluation, we can look forward to full introduction of production units into the operating forces. Only then may it be stated that the long development effort has achieved its major objective. Meanwhile, the focus of development is being turned to ships of 1000-ton size wherein the Navy can finally achieve full exploitation of hydrofoil ships as wide-ranging, highly responsive deep-ocean combatants.

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