Hydrofoil Ship Design

By

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Preface

This paper is an attempt to pull together notes I have on a chapter of a text book on advanced ships that I was asked to write around 1981. When the publishing company chose not to print such a book, I put all my notes in a folder and filed it. Unfortunately, two or three critical sections have been lost in the intervening 22 years. Among the lost sections are those on the sizing of the ship and the design process for the foil system. I will attempt to reconstruct them the best I can. Fortunately, I found most the figures in another folder which should help jog my memory.. I will therefore concentrate my efforts on sizing and design of a foil system to meet certain specified requirements. I will also discuss a simple way of designing the first version of the control system algorithm, which was very successful on the ***Foilcat***. Since I had listed them in the original table of content, the design of the hull and propulsion systems will not be included in this paper. Much of the material for the history and subsystem state-of-the-art sections came from Reference 1

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A Hydrofoil* is a ship in which the hull is supported above the water surface by the dynamic lift of a foil system attached below the hull. The major reason to lift the hull of a ship from the water is, of course, to circumvent the constraints on high speed due to wave drag and frictional resistance of the hull. When the hull is lifted from the water and the weight of the ship is wholly supported by the foils, one can no longer depend on the hull to generate the restoring forces necessary to maintain the ship's attitude and stability. Such stabilizing and control forces, therefore, must be generated by the foil system. These forces can be achieved either *through active control of the lifting surfaces or through passive control by using a foil* configuration which is inherently stable. In order to discuss hydrofoils, it is essential that the fundamental differences of these two basic concepts of achieving stability and control of a hydrofoil are understood. This is perhaps best done by discussing the two basic foil system configurations used in hydrofoil ships. First, there is the surface-piercing foil system in which the lifting surfaces themselves penetrate the air/water interface as shown in Figure 1 below.

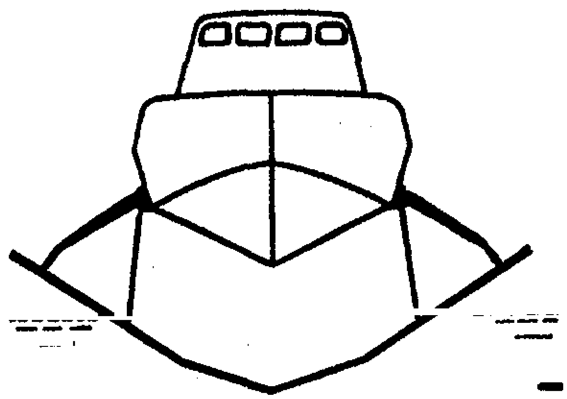


Figure 1. Surface Piercing Foil System

Such systems are inherently stable in that the lift generated by the foils varies direct1y with the depth of foil submergence; in other words, as they go deeper in the water, more lifting surface becomes effective thus increasing the lift which tends to return the ship back to its equilibrium height. This phenomenon is called "area stabilization". In the same manner, as the ship rolls, the outboard foil lift increases while inboard foil lift decreases, creating a moment to restore the ship to an unrolled condition. The degree of stability or stiffness can be altered by the nominal angle at which the lifting surfaces pierce the surface.. As can be seen, the surface-piercing foil system is inherently stable and closely coupled to the surface of the water. The degree of inherent stability is directly proportional to the degree of the coupling to the sea surface.

The other basic foil configuration is the fully-submerged foil system which places the lifting surface completely below the air/water interface as shown in Figure 2.

*Strictly speaking, the term hydrofoil applies only to the lifting surface and not the whole ship. In this paper "hydrofoil" will refer to the complete ship.

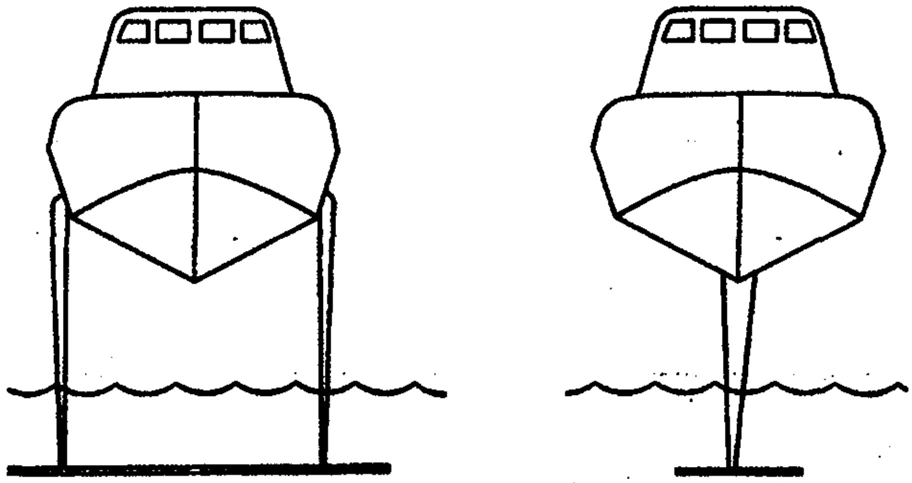


Figure 2. Fully- Submerged Foil System

In such a case, some type of control is needed to maintain flying height as the foil system has practically no sense of its position relative to the water surface*. In other words, with the fully-submerged foil system, the foils are essentially uncoupled from the surface. With the added complexity of a control system , one may rightly ask why one would chose a fully-submerged foil system. The reason is that with automatic control of the lift generated by fully-submerged foils, the foil system can be decoupled from the sea surface resulting in smoother operation and greater flexibility in heavy seas.

Another distinction which is useful to understand before proceeding, is the differences in basic hydrofoil configurations based on distribution of lifting surface area along the hull, as shown in Figure 3. In the "canard" configuration, the major portion of the load is borne on large foils located aft of the midship section. A smaller lightly-loaded foil is placed forward. The canard distribution is arbitrarily defined, as one in which 65- percent or more of the load is concentrated on the aft foil assembly. The opposite arrangement is referred to as the "airplane" or "conventional" foil configuration. Here the major portion of the foils is forward of the midship section. The "tandem" foil arrangement, lies between these two types . The load is borne about equally by the forward and aft foil. Generally speaking, satisfactory overall arrangements and satisfactory craft performance can be achieved with either a canard, airplane or tandem configuration. Selection of foil area distribution is, therefore, dictated primarily by such considerations as locating of major components, mission requirements, foil retraction requirements and type of propulsion system.

*There is a small stabilizing effect which results from the variation in lift with depth on a fully-wetted foil operating near the free surface (less than one chord depth) This effect, however, is too small to assure stability in even modest seaways.

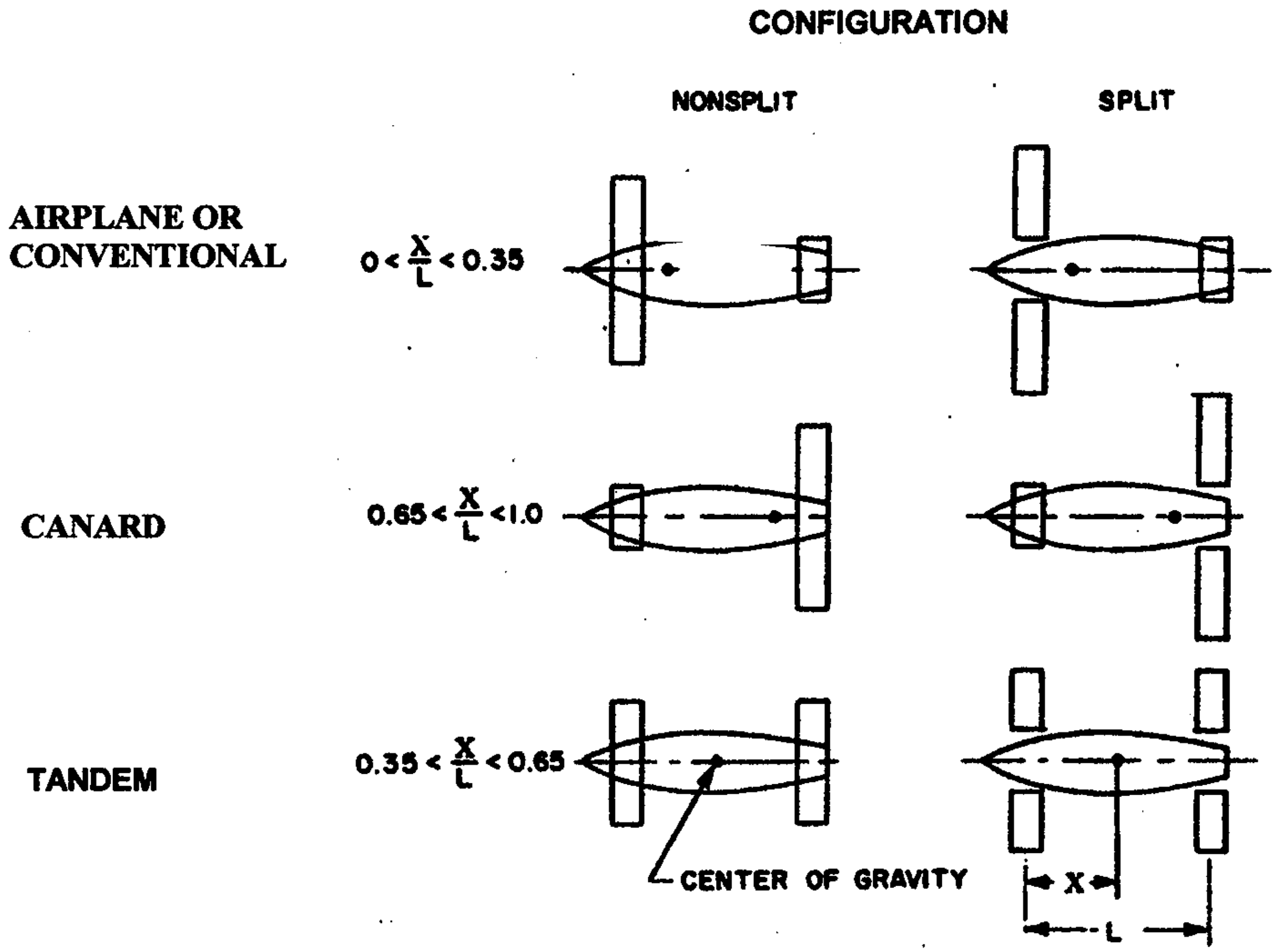


Figure 3. Definition of Foil Area Distribution

History

From the earliest part of the twentieth century, until the 1950's, the progress of hydrofoil technology has been one characterized by sporadic interest but very limited financial support. When one realizes that such famous inventors as Wilbur and Orville Wright and Alexander Graham Bell experimented with the hydrofoil concept, it is hard to believe that progress has been so painfully slow. Excellent summaries of activities during this first 50 years are given by Crewe[2] and Hayward[3] as well as many other authors and it is not my intent to go into detail of these historical aspects of hydrofoil development. Tabulated below are some key events.:

(1) 1906, Enrico Forlanini flew a hydrofoil with a ladder type (area stabilized) foil system at 38 knots on lake Maggiore in Italy.

(2) 1918, Alexander Graham Bell and Casey Baldwin, on their fourth refinement of the ,Forlanini foil system, flew the HD-4 at 61.5 knots on the Bras d'Or lakes.
3) 1936, Hanns Von Schertel achieved his first practical foil design from which the now famous Supramar boat was developed.
(4) 1953, Supramar PT-20, Freccia d'Ore enters commercial service.

As you read the history of hydrofoils you will find one common thread woven through the development of the hydrofoil concept, the search for a practical and controllable configuration. Control theory, electronic sensors and hydraulic servo actuators that we now take for granted were not readily available in those days. It is little wonder that the first really successful hydrofoils relied on the inherent stability of area-stabilized surface-piercing foil systems. Many early hydrofoilers, however, recognized the advantages of getting the lifting surfaces as far away as possible from the disturbing influence of the water surface. Even Baron Von Schertel, the father of modern day surface-piercing hydrofoils, spent eight years and built six test boats in attempts to stabilize fully-submerged foils before turning to the surface-piercing foil system for which he is so well known today. His early experiences are found in Reference 4.

Fully-submerged hydrofoil development lagged far behind the commercial exploration of the surface-piercing hydrofoils based on the Schertel-Sachenberg foil system until the advent of the ***Sealegs*** . In the mid 1950's, Gibbs and Cox, working with the Massachusetts Institute of Technology Flight Control Laboratory, developed for ***Sealegs*** an autopilot with an analog computer and a sonic height sensor. ***Sealegs*** with this autopilot provided the first real demonstration of the feasibility and advantages of a fully-submerged automatically-controlled foil system. The many hours of foilborne operation, much of it in rough water, produced valuable data which formed the foundation for the design of the U.S. Navy's ***High Point***(PCH-1.)The United States Navy, by 1960, was committed to the development and building of fully submerged hydrofoils. A detailed review of this program from 1960 to 1970 is given in Reference 1 This effort has produced five hydrofoil ships, culminating in the USS ***Pegasus***, the first of the PHM class of missile-carrying hydofoils. It is interesting at this time to note that the commercial surface-piercing hydrofoils have evolved over the past 20 years to a point where up to 80 percent of the ship is supported by a fully-submerged foil and only 20 percent is supported in the true surface-piercing area stabilizing mode. These ships use autopilots for stability augmentation and to improve the ride quality in a seaway. The 254-passenger ferry boat , R200, built by The Rodriquez Company in Messina Italy is an example of the latest surface- piercing commercial design.

Major Subsystem State-of-the-Art

Hydrofoil ships use the dynamic lift of submerged lifting surfaces to support their weight which in conventional ships is supported by the buoyancy of the hull. In this way the ship's hull can be lifted clear of the water, eliminating hull drag and the forces imposed on the hull by the seaway. However, these advantages of a hydrofoil are bought at a price. As with any dynamic lift vehicle (i.e., aircraft), hydrofoil ships are weight sensitive and must operate at relatively high speeds in order to generate the dynamic lift required to support their weight with a reasonable size foil system.

Weight sensitivity and speed coupled with the problems associated with operating in the worst of the marine environments (the air-water interface) place special demands on the ships' subsystems. Let us examine these often conflicting demands for each of the major subsystems and assess their present state-of-the-art.

Hull

The major reason for the employment of hydrofoils is, of course, to lift the hull from the water and circumvent hull restraints on high speed. Hydrofoil ships, however, spend a considerable portion of their life hullborne and must have an efficient hull form to keep the drag low up through takeoff. Total drag just prior to takeoff is a significant factor in establishing the power requirement and careful attention must be paid to the hull design to minimize this effect, Figure 4, shows a typical calm water drag curve for a hydrofoil craft with its significant "hump" prior to takeoff. Comparison is also made with a typical planning craft to illustrate the high-speed advantage of the hydrofoil even in smooth water.

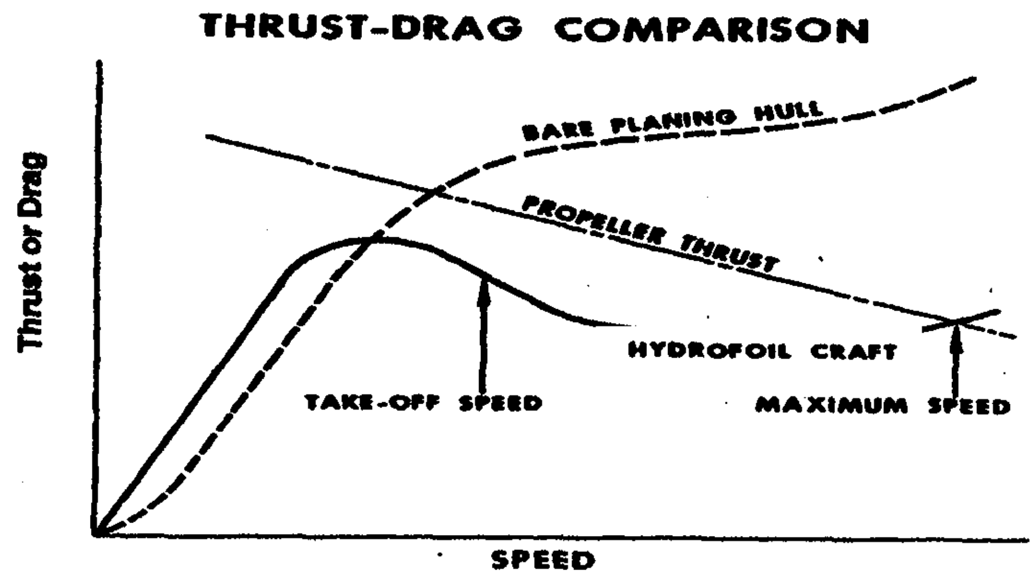
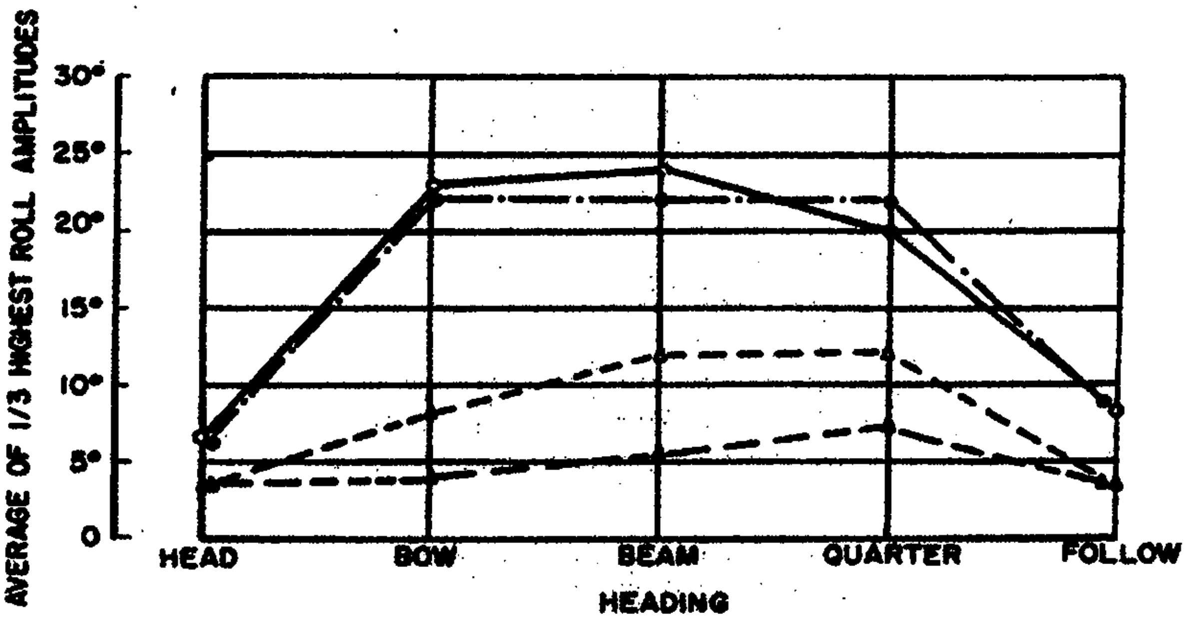


Figure 4. Typical Calm-Water Thrust-Drag Curves

In order to allow for additional takeoff drag which results from rough water, a power margin over smooth water takeoff requirements is required. Since the magnitude of this margin is a prime factor in the sizing of the propulsion system, it is essential that it not be arbitrarily over-specified. Tests in design sea states on well instrumented U.S. Navy hydrofoils show that 20 to 25 percent margin is ample for takeoff in sea state 5 in any direction.

An efficient hullform requires a narrow beam, whereas a righting moment large enough to avoid disaster in case of a hard over-roll control failure when foilborne dictates a wide beam. Cresting the tops of waves while foilborne points toward a deep vee forward and high dead rise.

Another major consideration in hull design is the requirement for good seakeeping characteristics in a heavy sea. If hydrofoil craft are to operate unrestricted in the open ocean, they must be capable of surviving storm seas in the hullborne condition. Furthermore, in certain missions, it may be expected that the hydrofoil will spend the major portion of its operating lifetime in the hullborne mode. Thus, it is essential that close attention be given to the hull seakeeping characteristics. With the foils extended during hullborne operation there is a significant effect on craft motion, particularly in the roll mode which is normally not heavily damped. This is shown in Figure 5 (from Reference 5) obtained from model tests on the U.S. Navy experimental hydrofoil ship, ***Plainview*** (AGEH). The strut/foil system gives hydrofoil craft hullborne motion characteristics of ships having much larger displacements



foils up, portside down **_ _ _ _ _ foils down, portside down**

_ __foils up, stbd side down **__ __foils down, stbd side down**

Figure 5. Predicted Hullborne Roll of AGEH in State 7 Sea Based on 5-foot Model Tests

Although a hydrofoil hull is basically out of the water when foilborne, it must operate much of the time hullborne. When one takes into account all of the design considerations enumerated above, the hydrodynamic design of a hull for a hydrofoil is not a trivial one. It requires careful balances and compromises of many conflicting requirements.

Structurally, the hull must have the strength to react to wave impact and crash landing in high seas at foilborne speeds, as well as react the concentrated loads at the strut attachment points. Weight considerations dictate light-weight materials. Cost, producibility (weldability), repairability, and resistance to sea water corrosion are significant factors in the selection of light-weight hull materials. At present, only the 5000 series aluminum alloys are felt to satisfy these criteria. Of these, 5456 A1 has been used almost exclusively in U.S. Navy hydrofoil hulls. H-321 and H-311, the type of 5456 A1 used, has been shown to exfoliate (or delaminate) and 5456-HI16 or 5456-HI17 is now recommended for hydrofoil hulls.

In using aluminum alloys for hull material, provision must be made for some form of cathodic protection. A sprayed zinc coating on the aluminum hulls of the U.S. Maritime Administration hydrofoil ***Denison*** and the ***Flagstaff***, PGH-I, has proven to be an excellent form of protection. Passive sacrificial zinc anodes strapped to the hull have proven adequate on other hydrofoils.

Regarding the weight criticality of the hull, one must ask what is a reasonable weight for a hydrofoil hull. Overall, hull weight fraction is a poor measure of structural efficiency as it depends on how densely packaged things are in the hull. An ore carrier, for instance, will have a far lower hull weight fraction than say a passenger steamer Hull weight per unit of enclosed volume is a far better measure of structural efficiency. Hydrofoil hull weights, as shown in Figure 6, presently run between two and three pounds per cubic foot of enclosed volume.

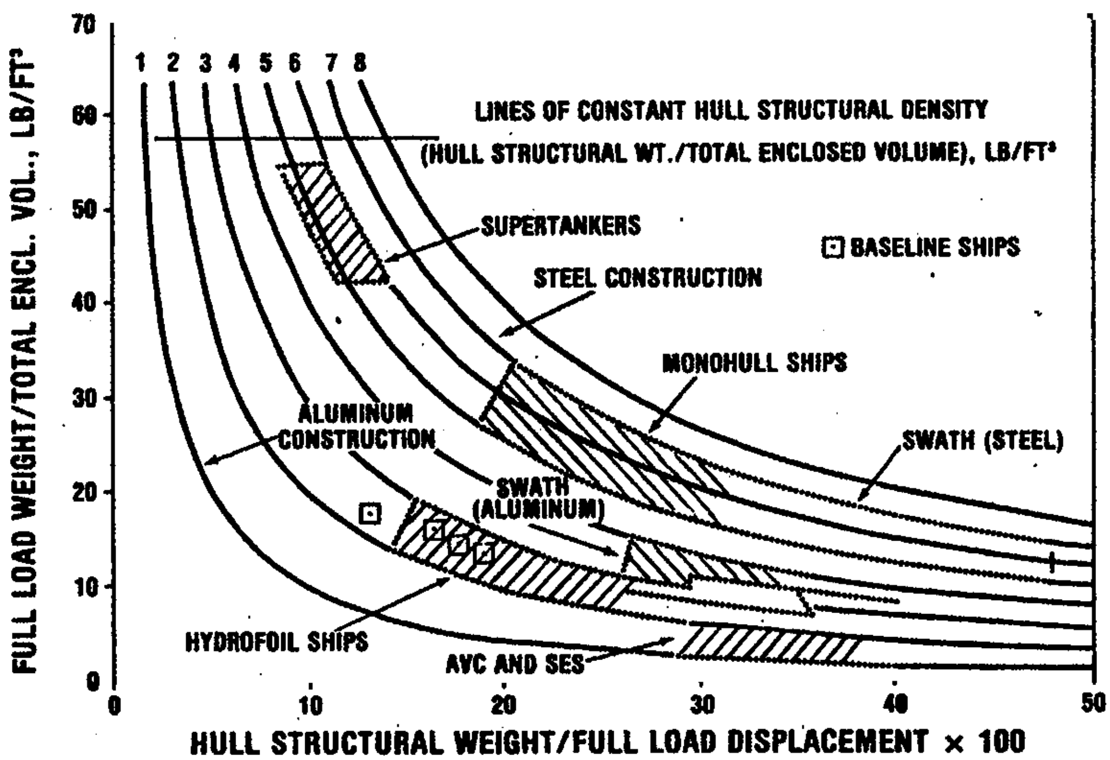


Figure 6. Relationship of Vehicle Density and Hull Structural Weight Fraction

When all the factors mentioned above are considered in trade-off studies, the design of a typical hydrofoil hull at the present time might be as follows:

- Length-to-Beam ratio: 4:1
- Hull Shape: Sharp V forward, 20 degree dead rise aft, hard chine planing surface.
- Material 5456 H-116 aluminum
- Construction: All welded frame and stringers, extended skin panels , extruded skin panels with integral stiffeners. Weight per cubic foot of enclosed volume: 2.5 pounds per cubic foot.

Struts and foils

The most apparent feature which distinguishes hydrofoil ships from others is the strut-foil system. The two basic types of foil systems, surface-piercing and fully-submerged have already been discussed in some detail. Another major distinction which needs to be made relates to maximum speed. The major obstacle to achievement of high sustained speeds in water is the occurrence of cavitation. High-velocity flow around struts, foils, and other appendages is attendant with a reduction in local pressure. When the total pressure at a point in the liquid drops below vapor pressure, cavities form with resulting radical alterations to the flow characteristics. Much above the speed of the onset of cavitation, a radically different approach must be taken in designing the foil system. A distinction must be made, therefore, between "subcavitating" and "supercavitating" configurations.

The hydrodynamic characteristics of subcavitating hydrofoils are very similar to subsonic aerodynamic characteristics of aircraft wings. Thus, it has been possible to adopt much of airfoil theory and techniques in their design. For hydrofoils which are to operate in the subcavitating regime, the problem is to develop foil configurations having sufficient strength, minimum weight, and maximum lift-to-drag ratio, while at the same time extending the critical cavitation speed to as high as practical. The achievement of high cavitation inception speeds is made more difficult by flow interactions at foil, strut, and pod intersections; effects of craft motion in a seaway; surface roughness, discontinuities; and the orbital velocities present in surface waves. In addition, at high speed, another phenomenon called ventilation occurs wherein air from the free surface is pulled down into the low pressure regions of a lifting surface. Ventilation usually occurs suddenly and causes a large rapid change and, in some cases, reversal of the hydrodynamic forces. Ventilation is a critical problem in the design of surface-piercing foils and struts which are subject to angles of attack. Since hydrofoil craft depend on the struts for their directional stability, sudden ventilation of a strut can drive the craft into a yaw divergence. Although the mechanism of ventilation and the laws governing scale effects are not yet completely understood, enough progress in the understanding of the phenomenon has been made to formulate criteria for avoiding strut ventilation.

Two basic rules should be observed if strut ventilation is to be avoided for speeds below 55 knots:

(1) The as-built surface of the strut must accurately adhere to the design contour and be smooth. Strut ventilation is almost always preceded by local cavitation; therefore, since an accurately-made strut is less prone to cavitate it is also less likely to ventilate.

(2) The angle of attack of the strut with respect to the flow velocity should be held to a minimum. By using only 100- percent coordinated turns for maneuvering and limiting the rate at which rudder can be applied, the angles of attack and thus hydrodynamic forces on the struts are minimized.

For surface-piercing foils. however, it is obvious that the second of the above criteria cannot be applied. The extent of the ventilation can be controlled, however, by placing chordwise fences along the foil to block the flow of air down the foil and keep the foil fully wetted.

Thus far, most foil and strut section shapes have been those selected from the NACA design literature such as the 16 or 63 series. These sections have characteristically flat pressure distributions and provide maximum lift within limits of cavitation inception. From this standpoint, bearing in mind the 800-to-one ratio of water and air densities, it appears that under ideal conditions, a foil loading of about 1600 pounds per square foot (PSF) is about the maximum attainable without cavitation. In practice, considerably low loadings of the order of 1200 to 1400 PSF must be employed if cavitation is, in fact, to be avoided. Furthermore, it appears that speeds much above 45 knots will always be associated with some cavitation unless extreme care is taken in the design and fabrication of the foil system. In the speed regime between about 45 and 60 knots one can consider the possibilities of living with cavitation, at least for short periods of time. One possibility that is under investigation is the introduction of air at joints of cavity formation either by natural ventilation or forced air injection. Such techniques reduce or eliminate cavitation damage to materials, and also give promise of significant decrease in noise production. They do, however, increase the complexity of system design and also result in some penalty in drag.

Another technique under investigation is designed to eliminate or ameliorate the radical changes in flow characteristics when cavitation occurs. By proper design of fully-submerged foils, cavitation can be caused to occur first at the tips of the foils. As speed increases, the cavitating area enlarges smoothly toward the wing root. This design is referred to as a "transit" foil. Although this type of transition should be achievable, successful designs have not yet been demonstrated.

At speeds above 60 knots we enter a design area which can no longer be classed as state-of-the-art even though a significant fund of knowledge has been accumulated toward the solution of hydrodynamic problems. At present, there are two basic approaches to high-speed foil design. One involves the use of so-called "supercavitating" sections and the other the use of fully-wetted, base-vented sections. Typical designs are shown in Figure 7

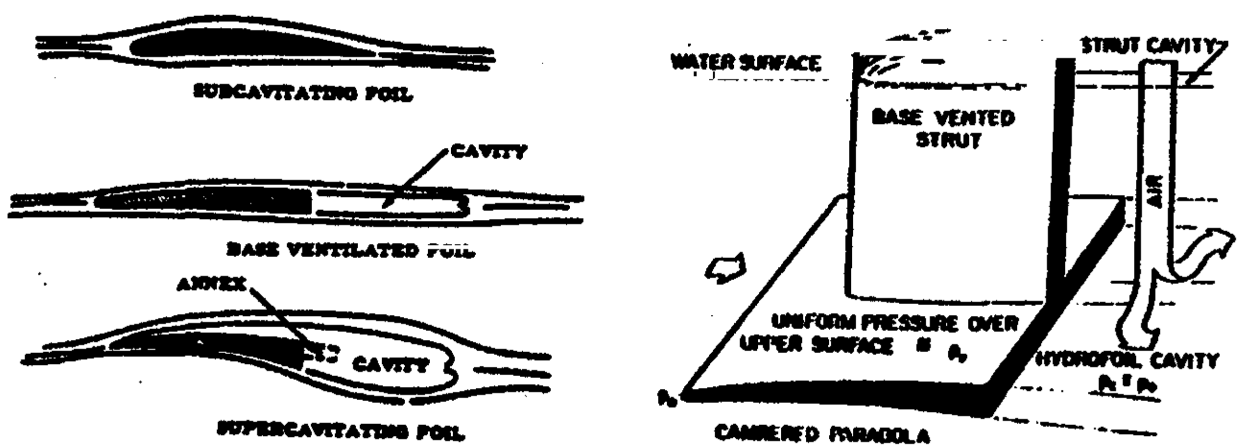


Figure 7. Subcavitating, Supercavitating , and Base Ventilated Foil Sections

In the supercavitating foil design, the sharp leading edge causes the formation of a fully developed cavitation cavity over the entire upper surface of the foil. Cavity collapse occurs well aft of the trailing edge and problems of buffeting and erosion are thus avoided. The propensity of the cavity of a supercavitating foil to ventilate when near the free surface, which happens often in a seaway, is a major problem. To preclude this problem and stabilize the cavity, air through a reliable path is vented into the cavity to stabilize it. Such foils are always vented and are called superventilated foils. Other difficulties with supercavitating or superventilating foil designs still to be resolved are, the high angles of attack to generate the cavity reliably, the structural strength of the thin leading edge, the difficulties in achieving reliable and effective control, and the problem of generating high lift at low speeds associated with takeoff. The last of these problems has been attached by Shen, (Reference 6) wherein he has designed and tested a foil which remains subcavitating up to around 50 knots at which time a full span flap is hinged down or near the mid-chord of the lower surface and a small full-span spoiler is raised near the leading edge on the top surface. This converts the subcavitating foil to a super-cavitating section Much work is still required to make the transition smooth and controllable.

In general, it appears that true supercavitating or superventilating foils offer the greatest promise at speeds above 80 knots. At speeds below 80 knots it presently is felt that fully-wetted base-vented designs may be more practical. The development of sections with decreased cavitation and ventilating sensitivity to angle of attack and results of research in this area are encouraging. Generally superior lift-to-drag ratios can be expected of supercavitating sections in the 80-to-100 knot range but fully-wetted base-vented sections will be competitive at lower speeds. Fully-wetted, base-vented foils and struts have been successfully demonstrated on the foil test craft FRESH -1 (Foil Research Ship) at speeds up to 80 knots. It is clear, however, that much additional work, both experimental and theoretical, must be performed to develop an adequate capability for high-speed foil system design.

Materials

One of the most critical problem areas in the design of foil systems is that of materials. The selection of suitable materials having high strength, low weight, resistance to sea-water corrosion and cavitation erosion, and having acceptable fatigue properties, while at the same time not imposing unacceptable penalties in cost and difficulty of fabrication, presents a major challenge to the designer. To date, a considerable effort has been expended in the development of suitable materials, much of which has not been directly aimed at the hydrofoil problem even though the information on material properties thus obtained has been of great value to the foil designer. At the present time, a number of candidate foil materials have been identified, each of which calls for one compromise or another in comparison to ideal material properties. Candidate materials can be broken down into those which are noncorrosive and those which require a coating to resist seawater corrosion. Of the former, Inconel 718, 17-4PH, 15-5PH, and 6-2-1 Titanium are the most promising.

Inconel 718 is very resistant to corrosion, but expensive, very difficult to fabricate, requires post weld heat treat, and has relatively a low toughness.

17-4PH and 15-5PH are generally corrosion resistant, but have poor pitting and crevice corrosion resistance, moderately difficult to fabricate, requires post weld heat treat, and low toughness.

6-2-1 Titanium has excellent corrosion resistance, high toughness, requires no post weld heat treat, but is very expensive, difficult to weld and has half the modulus of elasticity of steel. Of the corrosive materials, the HY steels combine most the features desired. HY-80 and HY-IOO have moderate strength, high toughness, good fatigue properties require no post weld heat treat, and are relatively cheap and easy to fabricate, but are not corrosion resistant and require a protective coating. HY-130 has high strength, moderate toughness, good fatigue properties, requires no post- weld heat treat, is somewhat more difficult to fabricate than HY-80, but, again, is not corrosion resistant and requires a protective coating. The otherwise excellent properties of the HY-series steels can only be realized if they are properly protected by a coating. Dry retraction of the struts and foils ameliorates the coating problems as it allows for routine repair and maintenance of damaged coatings before the flaws grow. Areas where coatings require care in application and maintenance are the leading edges, faying surfaces, over fasteners and strut-foil-pod intersections. With proper application, and routine maintenance, coatings can be made to last a year or two between major refurbishing.

There is another material development which offers the possibility of combining the corrosion resistance of Inconel with the excellent properties of HY-steels. This material is made by roll cladding thin (2 to 4 mm) sheets of Inconel 625 to the HY-130. These materials are weld compatible, and the surface remains corrosion resistant as long as the last few passes of weld is made with inconel. Forming, welding, and general fabrication techniques has to be tried, tested, and documented before this material is ready to manufacture strut-foils in production.

Hvdroelasticitv

In the area of strut and foil structure, one of the major considerations is the avoidance of hydroelastic problems. "Hydroelasticity" is concerned with phenomena involving mutual interactions among inertia, hydrodynamic, and elastic forces. The simplest forms of hydroelastic instability, divergence, and control reversal, involve only hydrodynamic and elastic forces These are relatively easy to predict for subcavitating foil designs using aerodynamic experience. For supercavitating sections these can be predicted from experimentally derived lift and moment curve slopes

The most complicated form of hydroelastic instability is flutter. Whereas the problem of torsional divergence and control reversal involved only the hydrodynamic and elastic forces, flutter involves also the inertial forces of both the foil system and the fluid medium. Flutter analysis requires a knowledge of vibration characteristics, mode shapes, and over-all damping and it may be stated with some confidence that flutter is currently the least tractable of hydrofoil hydroelastic problems. Since flutter can cause a catastrophic failure of the foil system with possible damage to the main hull structure, a careful consideration of this problem area is essential.

Naturally, the first attempts to predict flutter speeds on hydrofoils relied on aeroelastic theory which had been verified on aircraft for high mass ratios (mass of wing to added mass) applicable to aircraft. The theory had not been refined or verified for .the low mass ratios applicable to water. Dr. Yuan-Ning and Peter Besch (References 7a, 7b, 7c) have extended their work down into this region and obtained good agreement with the limited experimental data available. As a result of their work, the large safety factors on flutter speed due to ignorance have now been greatly reduced for subcavitating hydrofoils. In the case of high-speed supercavitating configurations, however, there is a notable lack of confidence in our ability to predict the occurrence of hydroelastic instabilities. This is particularly true in the case of leading-edge flutter of supercavitating foil configurations. Because there does not appear to be a requirement for hydrofoils in the supercavitating speed regime, work on Hydroelasticity for supercavitating struts and foils is not being actively pursued.

Propulsion

The three major components of the propulsion system are the prime mover, transmission, and thrust producer. For small craft, a single system may be adequate; however, the conflicting requirements for hullborne and foilborne operation of Navy hydrofoils generally dictate a separate system for each mode.

Because of their lower first cost, higher efficiency, and flexibility of operation, diesel engines are generally employed for hullborne propulsion. The steady reduction in fuel consumption of small gas turbines is reaching a point where they are now becoming a strong competitor for hullborne power

Prime Movers

Lightweight diesel engines, because of their low cost, familiarity for the operators, and high mean time between overhauls, are used for foilborne power on most commercial surface-piercing hydrofoils which operate at or below 35 knots. When speed requirements are increased to say 50 knots, the power requirements increase 2 to 3 fold which puts the power beyond the capability lightweight diesels for hydrofoils of over 100 tonnes. Foilborne propulsion of large, high-speed hydrofoil craft has been made possible only through the development of the marinized gas turbine engine. Existing aircraft jet engines have been slightly modified as gas producers and coupled with newly-designed free-power turbines to permit conversion of jet power to mechanical power. These engines are available in sizes ranging up to 35,000 HP with specific weights of about 0.5 lb per horsepower. Blade cooling techniques have made possible the use of high turbine inlet temperatures which has brought the fuel consumption of gas turbines down to 0.4 lbs per horsepower-hour, close to that of diesel engines, as is shown in Figure 8

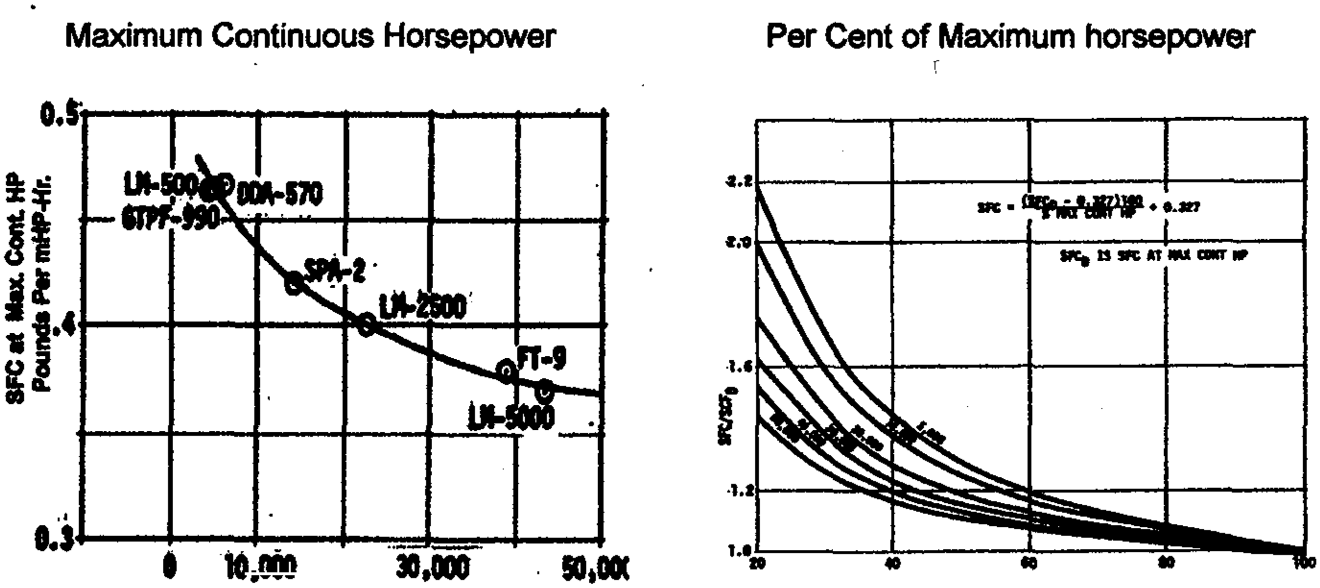


Figure 8. Full- Power Specific Fuel Consumption as a Function of Power

Thrust Producers

The selection of a thrust producer for hydrofoil craft is complicated by a number of unique design factors. Requirements for high power at low speed associated with the takeoff condition conflict with requirements for high power at high speed during foilborne operation (see Figure 10). Furthermore, although the current maximum speed range of interest is high by comparison to displacement ships, it is not high enough to make attractive the use of such devices as gas jets or air propellers due to their low efficiency. The high-speed test craft FRESH-I does employ a turbofan engine for propulsion but this selection was made to avoid interference with test foil systems. As for the air propeller, the large diameters required for the hydrofoil application preclude their use. This leaves water propellers and waterjets as the two principal candidates for hydrofoil propulsion. For speeds up to about 40 knots, the subcavitating water propeller is, by far, the most efficient device for producing thrust with propulsive efficiencies as high as 0.8 being attainable. At speeds much above 45 or 50 knots, however, it is virtually impossible to avoid the inception of cavitation with attendant loss in efficiency, erosion of blade material, and high radiated noise. A nominal increase in cavitation inception speed can be achieved by very careful design using thin blade sections of high-strength material; however, the problems of design are made more difficult by the adverse effects of strut/foil/pod interaction and the orbital wave velocities near the free surface. This has led to the development of transcavitating, supercavitating and super-ventilated blade sections Several families of transcavitating and supercavitating propellers have 'been developed and some designs have already been applied in practice. A 3-bladed supercavitating propeller of titanium on the ***Denison*** and 4-bladed supercavitating propellers of titanium on the AGEH-I have proven successful. A transcavitating propeller, designed and built by ***Kamewa***, was proven successful on the ***Flagstaff.***

Waterjets

Problems encountered with the gear transmission systems in early hydrofoils led to the interest in and the development of waterjet propulsion systems Such systems, see Figure 9 , typically consist of an inlet water duct, a pump, and an above-surface waterjet exhaust.

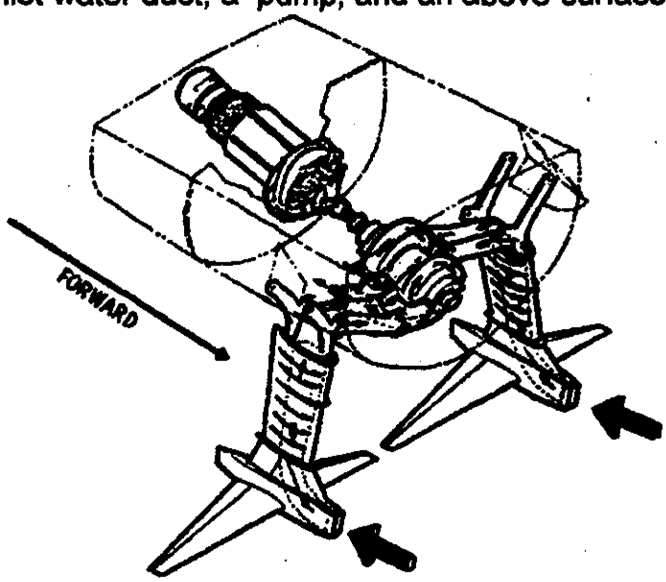


Figure 9. PGH-2 Propulsion System

Heavily loaded gears and long transmission shafts are thus eliminated and the number of moving parts is substantially reduced. This simplicity, how ever. comes at a considerable increase in required power, about 20% at 50 knots to about 100% higher at takeoff speed. This is demonstrated graphically in Figure 10 which shows the distribution of power in a typical 50- knot waterjet driven hydrofoil.

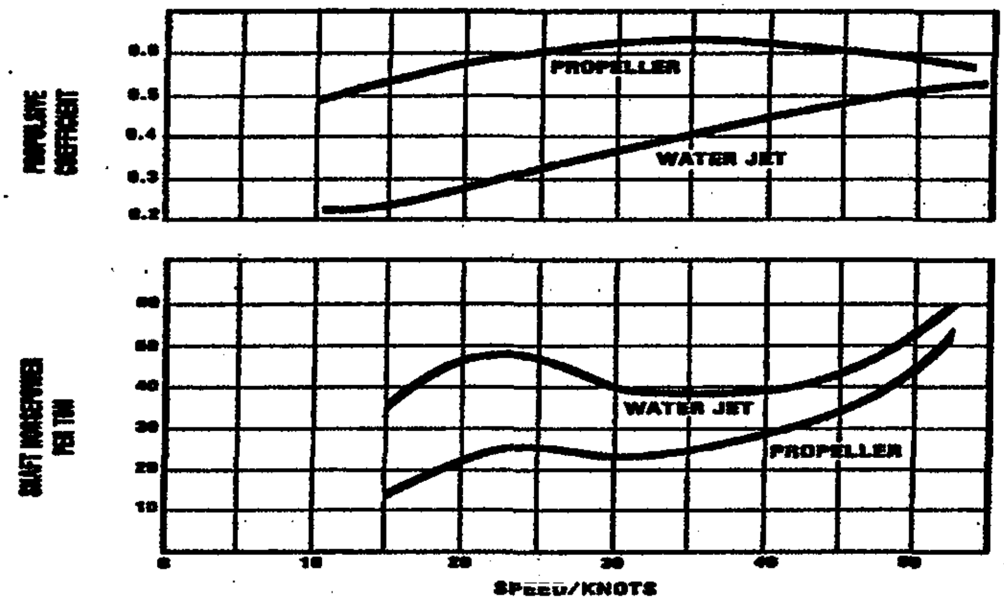


Figure 10. Comparison of Power and Propulsive Coefficient for a Typical Hydrofoil

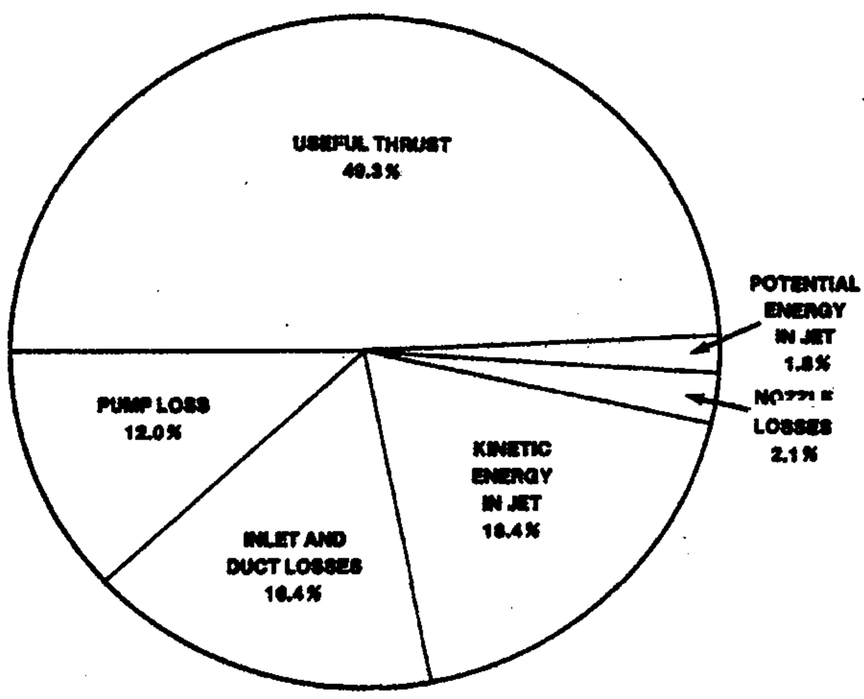


Figure 11 . Power Distribution of a Typical Waterjet driven 50- knot Hydrofoil

One may question why a waterjet for a hydrofoil has a propulsive coefficient of only 0.5 compared to 0.62 for a waterjet-driven high speed hydrofoil catamaran such as the Norwegian ***Foilcat.*** The answer is that, in a catamaran with their high deadrise hull, they do not have to fly as high out the water therefore vertically lift the water a shorter distance. They also can have a larger inlet allowing the waterjet to have a larger mass flow rate going through the system, resulting in a lower jet velocity. Since the losses are proportional to the velocity squared it is more efficient to have a high flow rate and a low jet velocity ratio (jet velocity/ ship velocity).

For a hydrofoil, however, there are major restraints. The mass flow rate is limited by strut thickness. Increasing the strut thickness increases the drag and the weight of water in the strut and hull above the surface of the sea. Careful trade-off studies must be made to achieve the best the balanced design. These studies must assess the interaction of strut size, inlet area, drag, efficiency, and the fuel required to meet the range requirements.

When one considers the weight of water within the system, a waterjet system is heavier than a comparable gear-driven propeller system. The PGH-2 has demonstrated that the simplicity of a waterjet makes for an extremely trouble-free and reliable propulsion system. Waterjet propulsion also results in a significant reduction in radiated noise compared to conventional transcavitating or supercavitating propeller systems. Compared to a well-designed subcavitating or superventilated propeller system, it is doubtful that waterjet propulsion would offer any reduction in radiated noise.

Transmission Svstems

In order to use the water propeller as a foilborne thrust device. it is necessary to provide a transmission system to span the long distance between the prime mover and the propeller. The problem is formidable in that it involves transmitting perhaps up to 30.000 HP with a six-to-one reduction of rotational speed from the gas turbine to the propeller, and provision for complete watertight integrity throughout the submerged portion of the system. The problem is further complicated by the desire to provide the capability for retracting the foil system.

Commercial surface-piercing hydrofoils have used angle-shaft drives to transmit the power from the prime mover to the propeller. Their power and rotational speed reduction are relatively low. With their relatively higher power, the U.S. Navy has concluded that the right-angle bevel gear drive represents the best choice at the current stage of development.
This type of "zee" drive was employed in the MARAD hydrofoil craft ***Denison*** and successfully demonstrated the capability of handling 13.000 HP through a single shaft and single mesh bevel gear. A similar system is employed in the ***High Point***, PCH-1 where 3000-HP is transmitted through a single shaft and a split -bevel arrangement in the pods to distribute power to the fore and aft propellers.

The AGEH is the highest power application of the Zee-drive transmission with more than 15,000 HP being transmitted through two drive shafts down each main strut to single propellers on the aft end of each pod. (see Figure 12). Comparing the ***Tucumcari*** (PGH-2) waterjet propulsion system (figure 9) to that of the AGEH shows the relative simplicity of the waterjet. Keeping water out of the lubricating oil system and failures in the lubrication system itself have been problems, but the major problem with U.S. Navy hydrofoil transmissions is that they have all been a one-of-a-kind system and have not had the advantage of design modifications based on actual use. There seems little question that, by proper engineering evolution, gear-drive systems can be produced with acceptable reliability, but probably never approaching that of a waterjet.

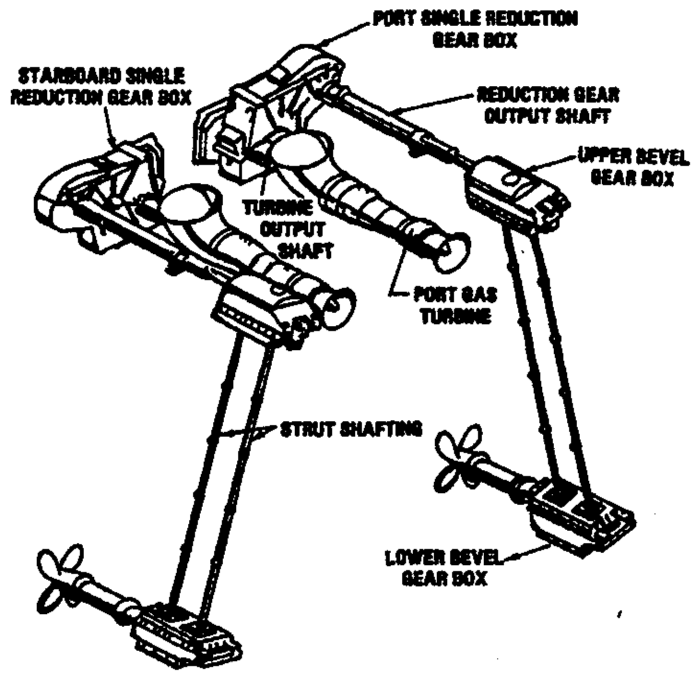


Figure 12. AGEH Transmission System

Ship Control

The ship control system comprises those components necessary to control the ship's speed, attitude, and direction and to supply, if necessary, dynamic stabilization. As with any dynamic lift vehicle, the control system of a hydrofoil can be divided into five functional areas: sensors, computer, actuation, force producer, and the vehicle itself. The vehicle and control system react to two inputs: the command and external disturbances (i.e., the seaway). These are shown in a typical block diagram in Figure 13 .

Hydrofoil craft having only surface-piercing foils, in general, do not employ an autopilot system with its associated sensors. The foils themselves act both as sensors and control devices by virtue of the change in forces and moments with depth of foil submergence. As already noted, this provides the persuasive advantage of extreme simplicity and high reliability. This simplicity is bought at the cost of rough water capability.

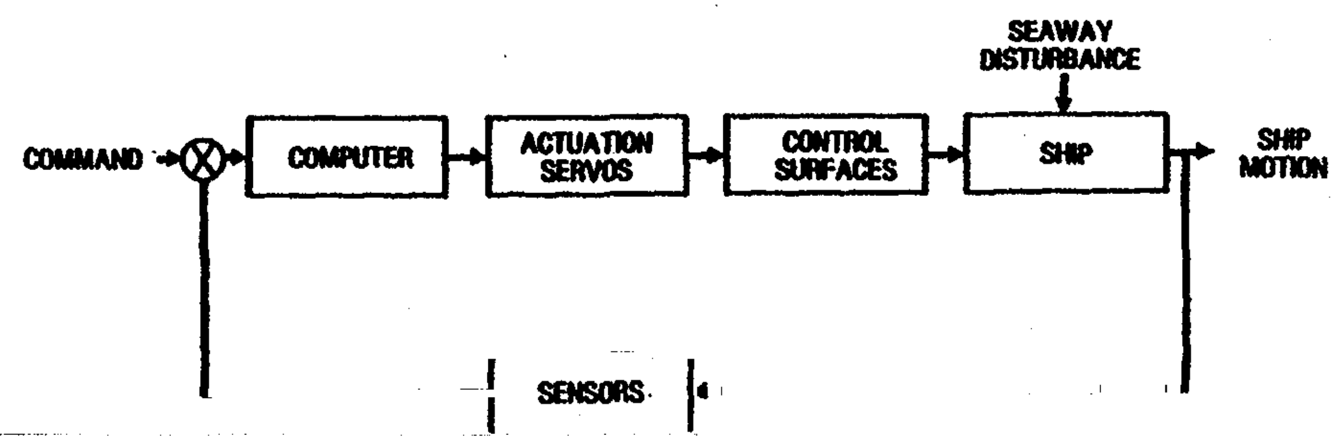


Figure 13. Hydrofoil Control System

In some cases, simple control augmentation may be added to surface-piercing systems in order to counter special stability problems that may occur due to particular mission requirements. This is the case in the design of the Canadian FHE-400 where controllable cathedral foil tips were employed to give added stability in the takeoff and low foilborne speed range. The FHE-400 was designed for a wide range of foilborne speed., considerably greater than usual design practice, where the takeoff speed is about one-half the maximum flying speed. This posed a special problem which required augmenting the stability at low foilborne speeds. Other systems employ a surface-piercing main foil and a smaller fully-submerged control foil in an attempt to buy some of the advantages of both configurations. The ***Denison*** *and Supramar's PT-150 are examples. These also had an autopilot to supply stability* augmentation.

It has generally been the conviction in the U.S. that ocean-going hydrofoil craft require fully-automatic control of submerged foils in order to provide acceptable craft motions. As a result, the main effort in this area was directed toward such designs. The validity of this philosophy has been verified through the exceptional rough water performance of the U.S. designed hydrofoils. This discussion, therefore, will be primarily constrained to the technical aspects of submerged-foil craft having some form of automatic control.

In flight, there are in principal, two modes in which the ship can operate in rough water as shown in Figure 14. If the hydrofoil is relatively large compared with the waves and its flying height is sufficient to permit the hull to travel in straight and level flight clear of the waves, the craft is said to "platform" with zero response. In the other extreme, if the hydrofoil is small compared to the waves, it is constrained to follow the surface. This is known as "contouring"

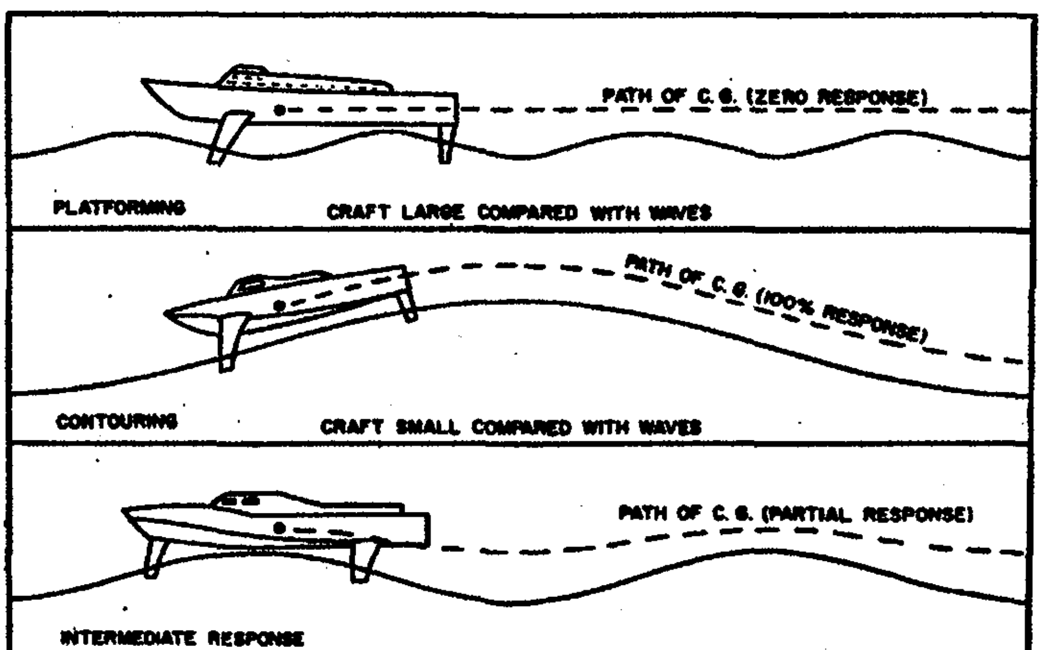


Figure. 14 Platforming and Contouring Modes

and ideally, a 100- percent response is required. With a hydrofoil having an autopilot and the ability to control lift, one has the option to select reasonable compromises between these two extremes and seek to provide minimum foil broach and maximum hull clearance without exceeding specified limits of craft motion and accelerations. The; autopilots of the U.S. designed hydrofoils have frequency-sensitive filters which make them tend to contour waves with a low frequency of encounter (large amplitude long period) and platform those with a high frequency of encounter (short period small amplitude.) For maneuvering hydrofoil there are fundamentally two modes; flat and coordinated or banked as shown in Figure 15.

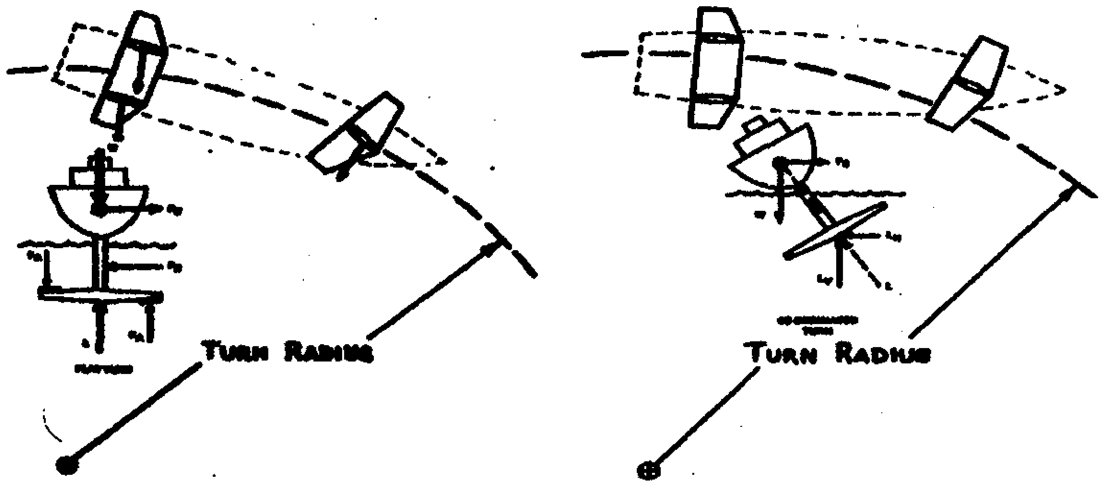


Figure 15. Flat and Coordinated Turn Modes

For a flat turn all of the side force required to overcome the centrifugal force must be generated by the struts, while for a fully coordinated turn, all of the side force is generated by a component of the lift vector of the foils. The fully-coordinated turn is favored over flat turns on most hydrofoils because:

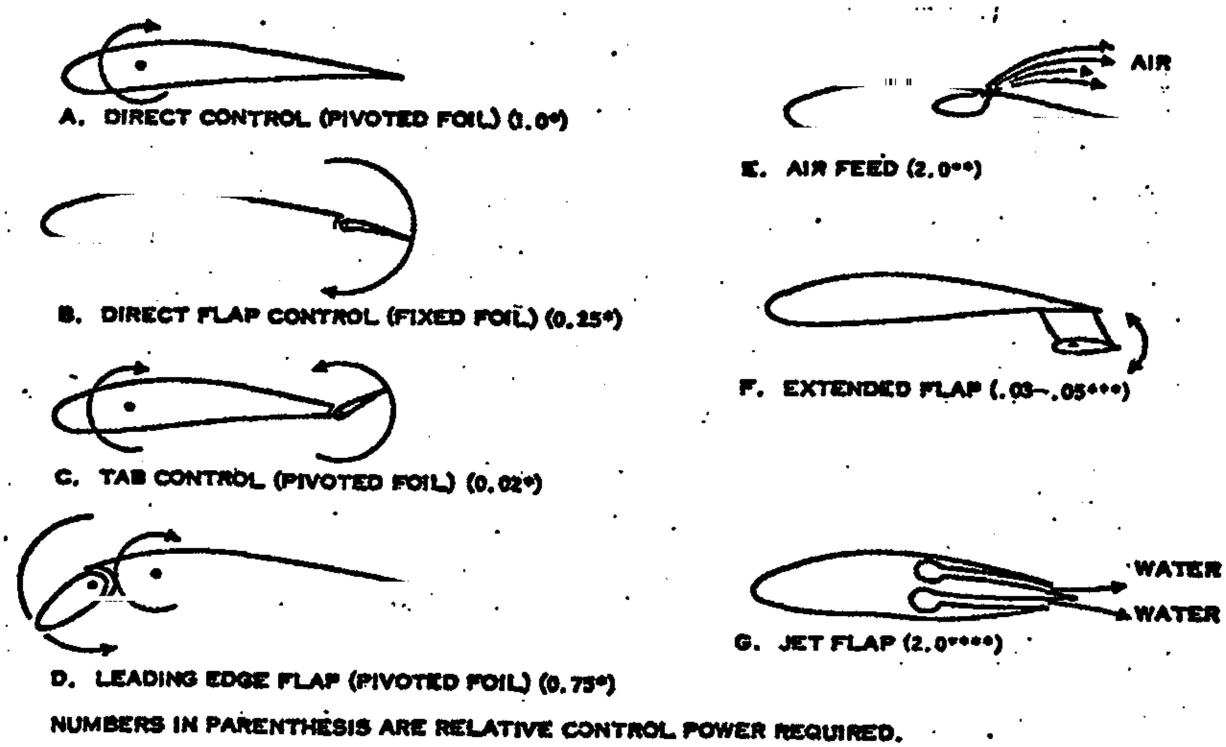
(a) The struts operate with essentially no angle of attack, thereby minimizing strut loads
(b) It is more comfortable in that the sensed acceleration vector remains normal to the deck
(c) Approximately twice the turn rate compared to flat turns can achieved.

Lift Control

Lift control can be achieved in many ways. Seven possible ways are shown in Figure 16.The relative power required to actuate each of these relative to full incidence control is listed in the figure. When choosing the type of lift control device for a hydrofoil, one must make a balanced judgment among mechanical simplicity, reliability, actuation power, range of lift control, field experience, and cost. Incidence and flap control have been well documented and proven acceptable on existing hydrofoils. Other lift systems which show the greatest promise, particularly for large (~1000 ton) hydrofoil ships, are:

(a) the trailing edge tab in which the actuation forces required to pivot the complete foil are supplied by the hydrodynamic forces on a small trailing edge flap.

(b) the extended flap in which a balanced flap is placed below the foil to put the flap in a high pressure region to avoid hinge line cavitation.



* based on Reference 9 . **based on 1965 NSRDC-SUPRAMAR Tank Tests.
*** based on the Boeing Co. estimate ****Based on Reference 10.

Figure 16. Lift Control Schemes

A clever and more recent mechanical system which is still in use is the "Savitsky Flap" invented by Dr. Daniel Savitsky of the Davidson Laboratory, and used by Atlantic Hydrofoils on

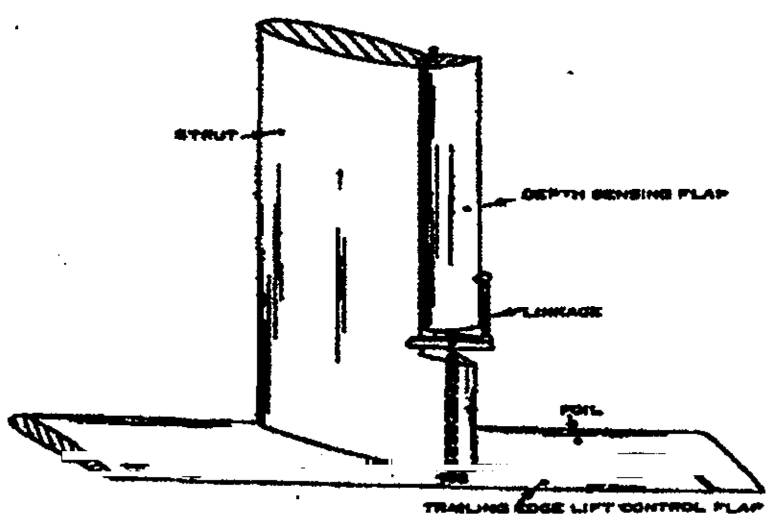


Figure 17. The Savitsky Flap

the ***Flying Cloud*** and the Korean Navy hydrofoil. The Savitsky Flap is a trailing edge flap, attached to the rear of the struts and nominally canted out at an angle. This flap is mechanically attached to trailing edge flaps on the foils as shown in Figure 17. At nominal flying height a portion of this flap is submerged. The hydrodynamic moment on the flap is reacted by a spring and the hydrodynamic moment on the trailing edge flap on the foil. If the craft goes deeper more of the Savitsky Flap is submerged and the moment on this flap is increased. This deflects the foil flap to increase lift and thus restore craft to proper flying height. The mechanism has both a bob weight and a shock absorber (damping) attached to it so that it can be tuned to basically ignore high frequency small waves and follow only the lower frequency larger waves.

Sensors

In the more sophisticated electronic control system described in more detail in References 15 and 16. Inputs to the autopilot are provided by electronic height sensors, accelerometers, position gyros, and rate gyros. For the hydrofoil applications thus far considered, the state-of-the-art in autopilot design is well ahead of that required for operational systems. This is due, in major part, to the rapid advances in technology stimulated by the space and aircraft program. Small accurate and reliable accelerators and gyros are available off the shelf with 2000-hour life ratings and these are suitable for hydrofoil control systems. Electronic sensing of local height of a hydrofoil above the water was originally done by ultra-sonic devices mounted on the bow. Dropouts were frequent so that two independent sensors were used. Special signal gating had to be incorporated to avoid interference from background noise such as gun firing, missile firing or low flying aircraft. To avoid this interference, most hydrofoils have replaced their twin sonic height sensors with a single radar unit which has been adopted from radar altimeters developed for missiles and helicopters.

Actuation Svstems

The efficiency of energy transfer, the low compressibility of the power transfer medium and the high power-to-weight ratio of hydraulic actuation devices makes the hydraulic system generally more attractive than pneumatic or electric actuation systems. Again, hydrofoils have taken advantage of aircraft industry developments of lightweight hydraulic system components. Using aircraft-type components and design philosophy, successful hydraulic systems up to 2000-horsepower have been built and used on hydrofoil ships. A summary of hydraulic systems and lessons. learned in the development of the AGEH system can be found in References 8 and 9.

Computers

Electronic control systems, to date, have all been of the analog type wherein craft motion sensor outputs are processed by the control computer and continuous proportional commands sent to the control surface actuators. Figure 18 shows the functional schematic block diagram of a hydrofoil control system.

Operating experience to date has shown that this type of control system is entirely adequate for subcavitating hydrofoils. With the rapid development and reliability of the mini computer, however, digital systems are replacing analog computers on hydrofoils.

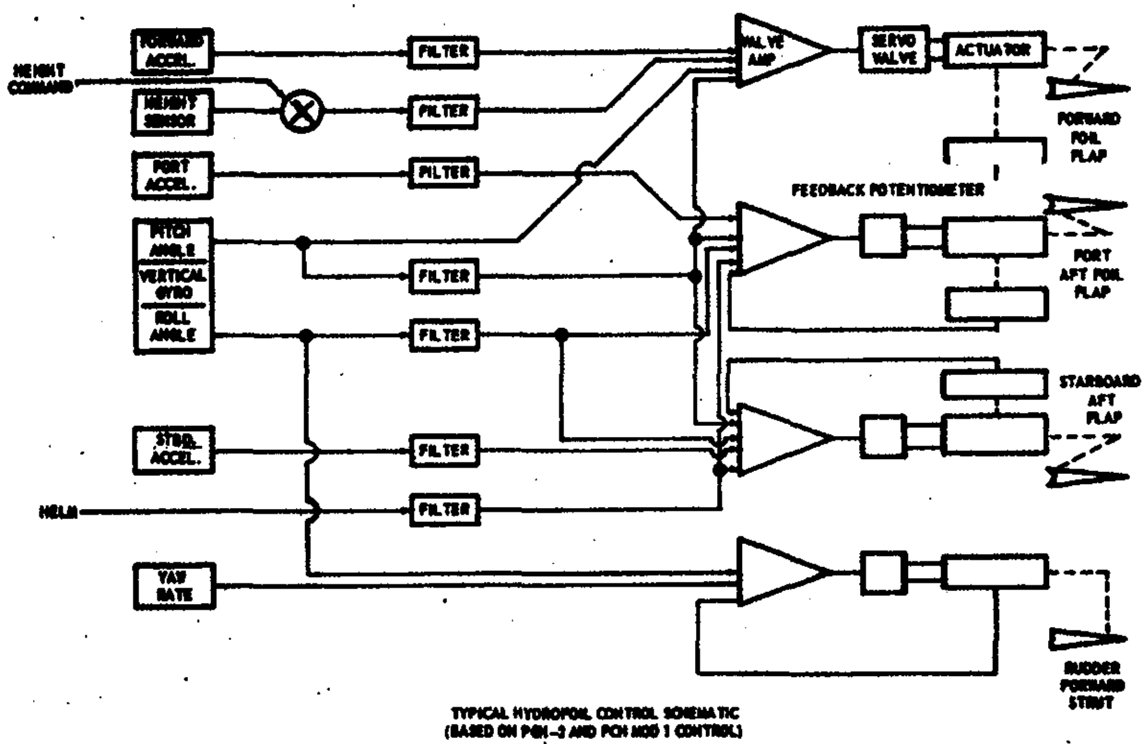


Figure 18 . Schematic of a Hydrofoil Control system

With a digital computer forming the core of the autopilot, it is possible to go to self-adapting control techniques, automatic self-monitoring, and have built-in diagnostic programs to assist in maintenance and repair. These can be done with relative ease by a digital computer

Auxiliarv Machinerv

This more or less miscellaneous area includes various auxiliary systems such as electrical generators, pumps, air conditioning, etc. Although there do not presently appear to be any major technical problems in this area, these systems do contribute a substantial portion of the total ship weight. As a result, there is strong reason to devote continued attention to means for reducing the weight of auxiliary system components. There are many possibilities for adapting modified aircraft practice in the design and specification of auxiliary systems. As a note of caution, one should remember that much aircraft equipment is designed for intermittent duty cycles, particularly 400 Hz. electric motors. Also, aircraft components are generally case ground, generally a forbidden practice for shipboard components.

Foil Desian

The design of the foil system for a hydrofoil involves the interaction of many variables. Fortunately the hydrofoil data bank ,Reference 10, has a wealth of parametric data and studies which can be used to help in this process. Some of these parametric relationships were developed using the HANDE program, Reference 11. The HANDE program assesses the effects of design changes and does all the dog work. It keeps track of all details, maintains consistency, assures all interactions are considered, updates all weights, and assures all stress levels are within established limits. In addition, HANDE does the numerous iterations needed to arrive at a converged design. An excellent description of the HANDE program is found in an appendix of Reference 12. a summary of which is found in Appendix A of this paper. Many of the parametric relationships based on actual ships and design studies are also shown in Reference 12 which forms the basis for much of this section. Let us demonstrate the design process by designing a foil system to meet the following specifications.

Specifications

Maximum speed..........50 knots
Minimum Speed..........30 knots
Payload.......................60 tonnes
Turn rate.................. .5 Deg/sec
Foil span.....................56 feet maximum
Range @40 knots.......2000 nautical miles

Rough water performance	
Maximum Accelerations	
Mid sea state 6	Sea state 5
At 43 knots	47 Knots
0.1 g's rms	.07 g's rms

As a starting point, let us rough-size the ship. To do this, the most accurate size estimate can be obtained from Reference12 in which twelve hydrofoils were designed using HANDE and the results were used to develop Figure 19 which gives the full-load displacement as a function of range for propeller-driven ships with a 10% payload Figure 19 gives a quick and relatively accurate starting point for the design process. A similar relationship for waterjet-driven ships has not been derived in HANDE. Figure 20, however, from an earlier study, gives the range-displacement relationship of water-jet driven ships with a 10% payload. As can be seen from this figure, for waterjet-propelled hydrofoils with a reasonable payload, ranges above 1600 miles are impractical and ranges above 1850 miles are impossible. Waterjet propulsion can therefore be ruled out for our ship.

From Figure 20, with a 60-tonne payload and a foilborne range of 2000 miles, we find that a ship with the full-load displacement of 675 tonnes should do the job. This means that we

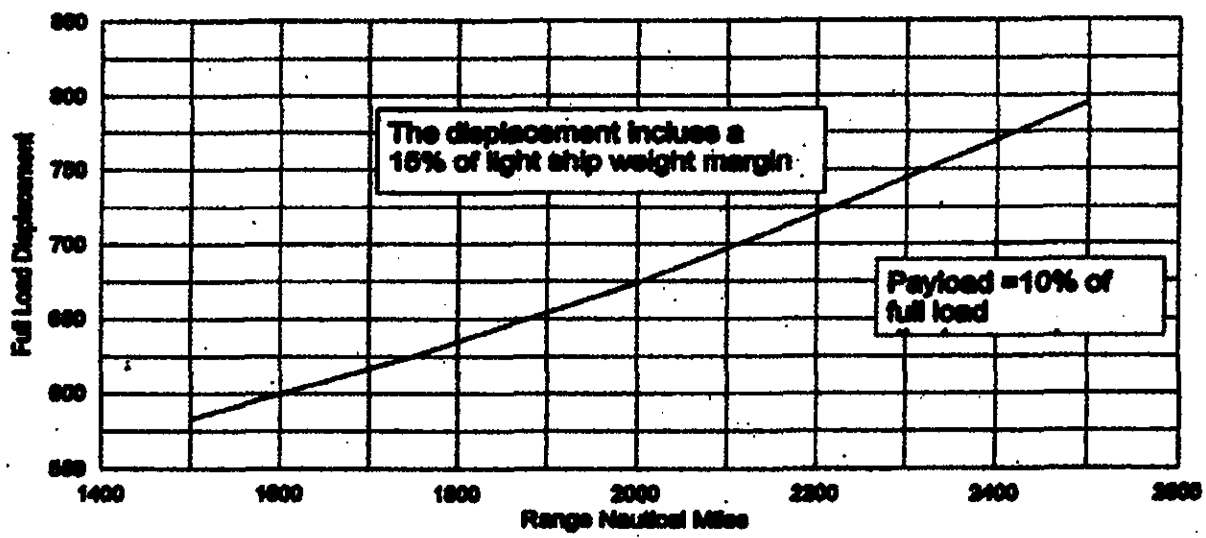


Figure 19. Ships Range as a Function of Displacement

need a foil system capable of lifting 675 tonnes. This lift force is made up of dynamic lift and the buoyancy of the foil-strut system at nominal flying height. The buoyancies of systems as a function of full-load displacement for a 8% thickness to chord ratio are shown in Figure 21. Subtracting the 25 tonnes buoyancy obtained from this figure from the full-load weight yields a dynamic lift requirement of 650 tonnes. At this point, the designer must decide on the lift distribution between fore and aft foils. A 50-50 distribution gives the minimum foil span but, unless a large portion of the payload is to be mounted well forward. It may be difficult to arrange the ship to achieve this distribution. Most smaller fully-submerged hydrofoils have a 33%-67% or 67%-33% distribution. Arbitrarily, at this point let us decide that on a 40%-60% distribution as a reasonable compromise between foil span and ship. arrangements. The relationship between span, foil loading, aspect ratio, and distribution will be discussed later on. For our ship, with a 40%-60% distribution, the forward foil must carry 260 tonnes and the aft foil 390 tonnes.

Everything we have done so far is to rough-size the ship so as to determine the dynamic lift for which the foils have to be designed. "Optimizing" the design of foil systems is such a multi-variable problem, I doubt if it will ever be formulated. Even if we could approach formulating it, engineering judgment still would be required in determining the cost function to which one "optimizes" the design. Let me attempt to guide you on one possible (not necessarily the best) path through the maze of foil design to illustrate and point out the major facets of the problem. The flow chart of the path we will pursue is shown in Figure 22.

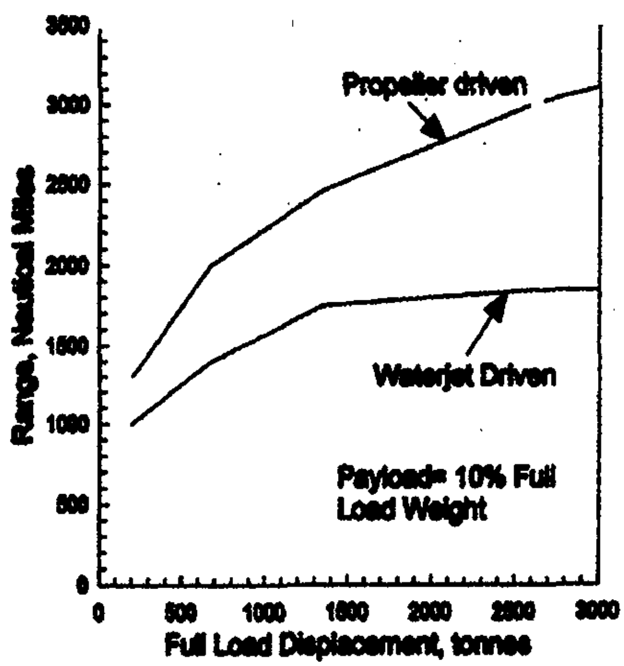


Figure 20. Range vs Displacement for Waterjet and Propeller ship

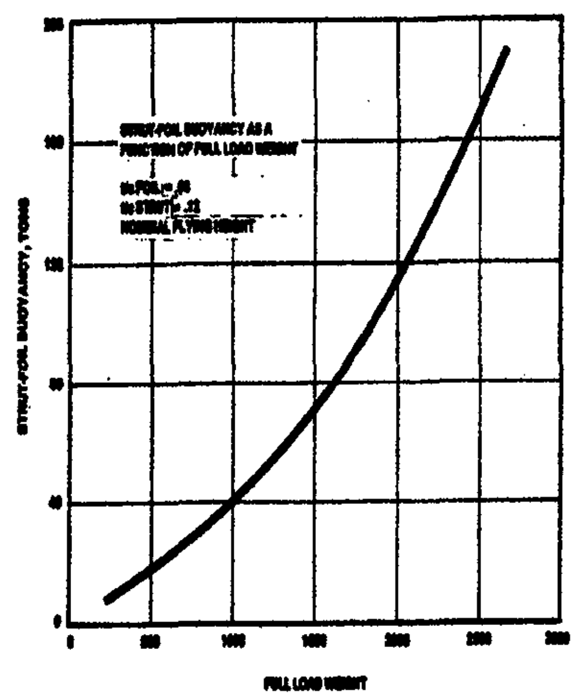


Figure 21. Buoyancy as a Function of Full Load Weight

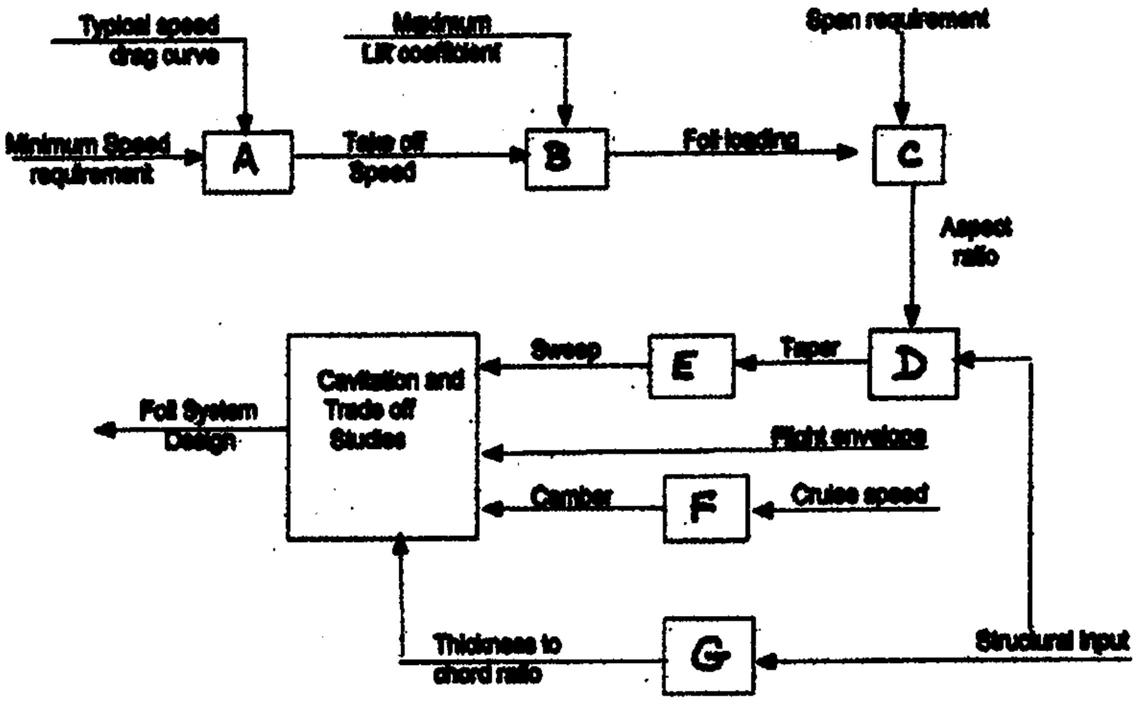


Figure 22. Foil Design Flow Chart

The Flow Chart, Figure 22, starts with the minimum speed requirements which will set the take-off speed requirements which will place an upper limit on the foil loading (foil lift divided by foil area). Next we will look at the effect of foil loading on efficiency to see if a foil

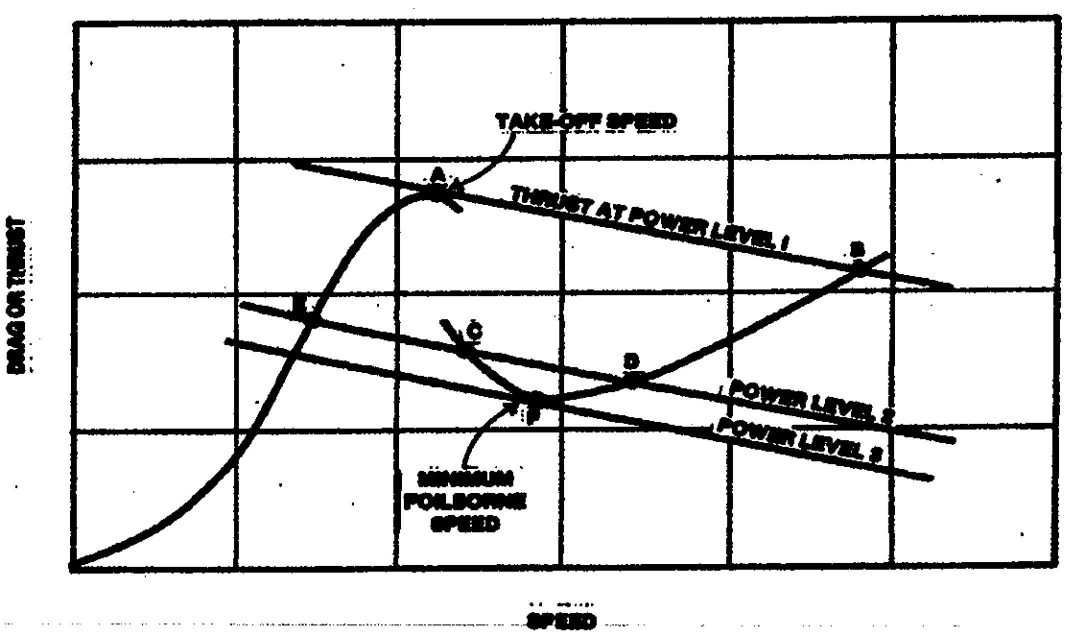


Figure 23. Relationship between Take-off Speed and Stable Minimum Foilborne Speed

loading below the maximum determined by take-off speed may have advantages in efficiency and cavitation. When the foil loading is chosen, aspect ratio, sweep, thickness to chord ratio, the taper ratio, and camber are determined. During the determination of the foil design the effect of variations in foil geometry and loading on the cavitation buckets, shown in Appendix B, are used to aid in the selected values. Next we will determine if a foil with this geometry and foil loading can be designed to be cavitation free throughout its core operating envelope. If not, what foil loading and geometry will give relatively the cavitation free operation.

A. The minimum foilborne speed of 30 knots is a specified requirement of the design. In order to fly with stability at the required 30 knots, it is necessary to have a take-off speed 10 to 15% lower. This is best illustrated by Figure 23 which shows the drag as a function of speed for a typical hydrofoil for several power levels. If we attempt to operate at point A, take off speed, and power level 1, the ship is obviously unstable in speed, since any positive perturbation in speed would reduce the drag, the ship would accelerate until we got to point B. However, point A is stable for any negative perturbations in speed. Point B is a stable point since any perturbation in drag or speed would create correcting forces. At power level 2, points D and E are stable, but point C is unstable as any perturbation in speed will either speed it up to point D or slow it down to point E. At power level 3, point F is really the opposite of point A in that it is stable for any positive perturbation in speed and unstable for any negative perturbation in speed. The minimum foilborne speed of a hydrofoil, therefore, is a speed just above point F which from US Navy experience is about 20% above take-off speed. In order to meet a minimum flying speed of 30 knots, the takeoff speed therefore must be about 25 knots. Since perturbations in drag or speed increase with increasing sea state, the minimum flying speed increases with increasing sea state. .

B. At 25 knots and with the maximum lift coefficient, the foil system must generate sufficient dynamic lift to raise the hull free of the water. The maximum lift coefficient that most .

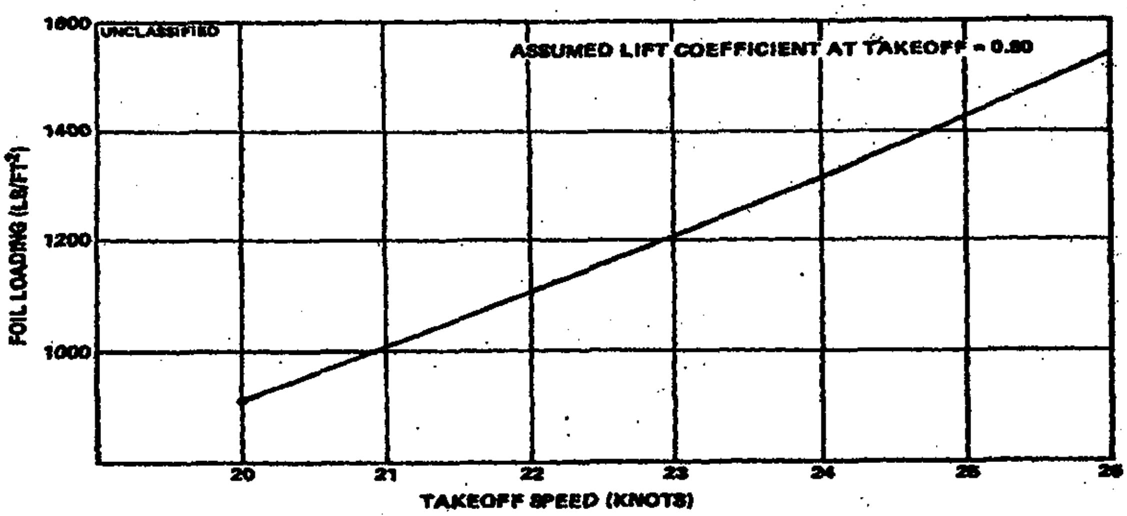


Figure 24. Takeoff Speed as a Function of Foil Loading

foils can generate is 1.0. At least 0.2 of this must be reserved for control, particularly roll. Figure 24 shows the maximum foil ding as a function of takeoff speed. For a takeoff speed of

25 knots the maximum foil loading is 1425 pounds per square foot. A lower foil loading results in a larger foil and under the span restraints, a lower aspect ratio and less efficient foil. A lower foil loading, however, reduces the lift coefficient needed for takeoff. This lowers the induced drag at take-off. This lowers the induced drag at takeoff that may be desirable if one has a marginal thrust margin.

C. The higher the aspect ratio the higher the foil efficiency. This is clearly demonstrated in Figure 25. The maximum aspect ratio possible is limited by the maximum span allowed. In our case, at a foil loading of 1425 pounds per square foot requires a foil area of 613 square feet. At a span of 56 feet, the mean chord must be 10.95 feet which makes the aspect ratio 5.11. For the forward foil, if we assume the full span of 56 feet, the aspect ratio would be 7.67. Structurally, such a high aspect ratio may cause a problem depending on the foil configuration. The most common and practicable of the possible foil configurations are shown in Figure 26. At this point in the selection of aspect ratio, (also with taper and sweep), tradeoff studies must be made between foil efficiency (lift-to-drag ratio) and the foil system structural weight. For instance, increasing the aspect ratio not only increases the lift to drag ratio, but also increases the structural weight of the foil system which reduces the amount of fuel available to meet the range requirement. To my knowledge the maximum aspect ratio used on any hydrofoil to date has been 6.

D. In Figure 26,. the bent foils shown are used aft and have sizable pods to hold the gear box for propeller-driven ships, or the inlets for waterjet hydrofoils. For the rest of this section we will limit ourselves to the inverted foil which is used for the forward foil in most hydrofoils. The next consideration in the design of the foil system is the taper ratio. Taper is used to lower the bending moment where it is attached to the pod. The pod in the forward foil system houses the flap linkage and helps separate the flow field around the foil from that of the strut. The PCH-1 uses no taper on the aft foil system and approximately a four-to-one taper on the forward foil system. This taper ratio reduces the bending moment at the pod by about 20%. The four-to-one taper on the PCH -1 higher than most hydrofoils use. The AGEH had a taper ratio of three-to-one which is a very reasonable one. As a starting point for our trade-off studies let us start with a taper ratio of three-to-one and an aspect ratio of 6.

E. As can be seen in in Appendix B, sweep has a very beneficial effect on the cavitation bucket. If we set the flap hinge line perpendicular to centerline of the pod it simplifies the flap actuation linkage. If we do this and assume an aspect ratio of 6 and a taper ratio of 3, the leading-edge sweep angle will be 15 degrees, and the quarter chord sweep will be 10.4 degrees. Another advantage to sweep is that it sheds debris much better than foils without sweep.

F. The next foil parameter that we must establish is camber. Camber-shaping of the centerline of foil gives a lift coefficient at zero angle of attack. By choosing a camber which produces the required lift at cruise speed (40 knots) with two-thirds fuel displacement, we will operate at the least drag at the speed with which we have to meet the range requirement. At foil loading of 1400 pounds per square foot and a speed of 40 knots this translates into a camber of about 0.3.

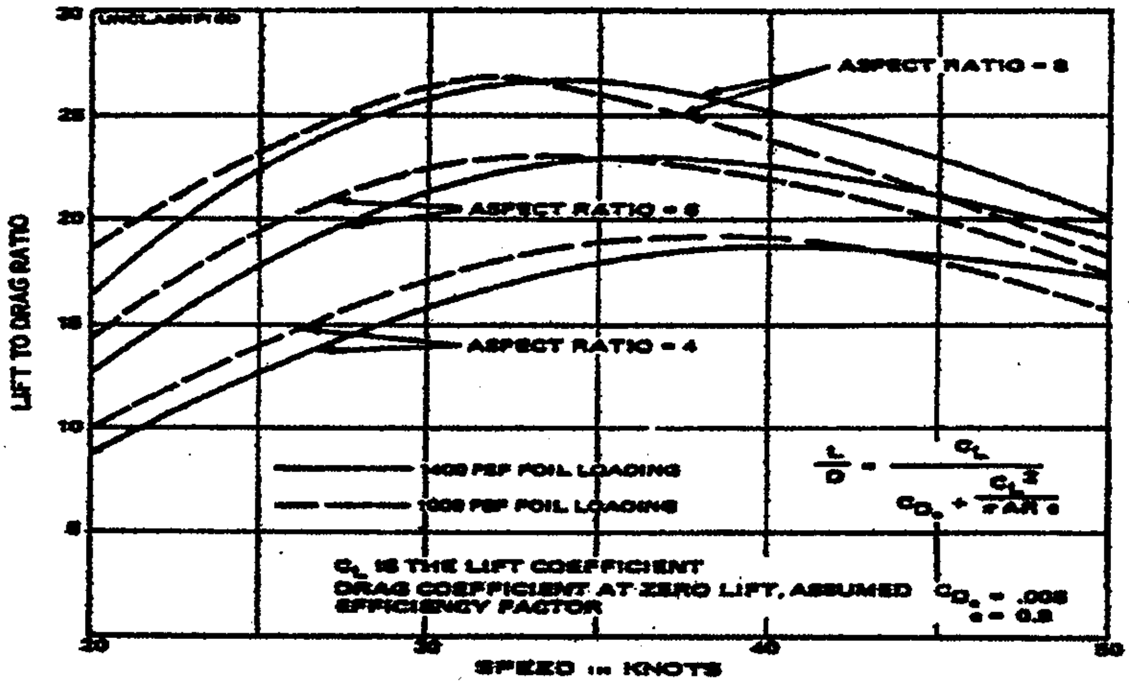


Figure 25. Lift-to-Drag Ratio as a Function of Speed at Different Aspect Ratios

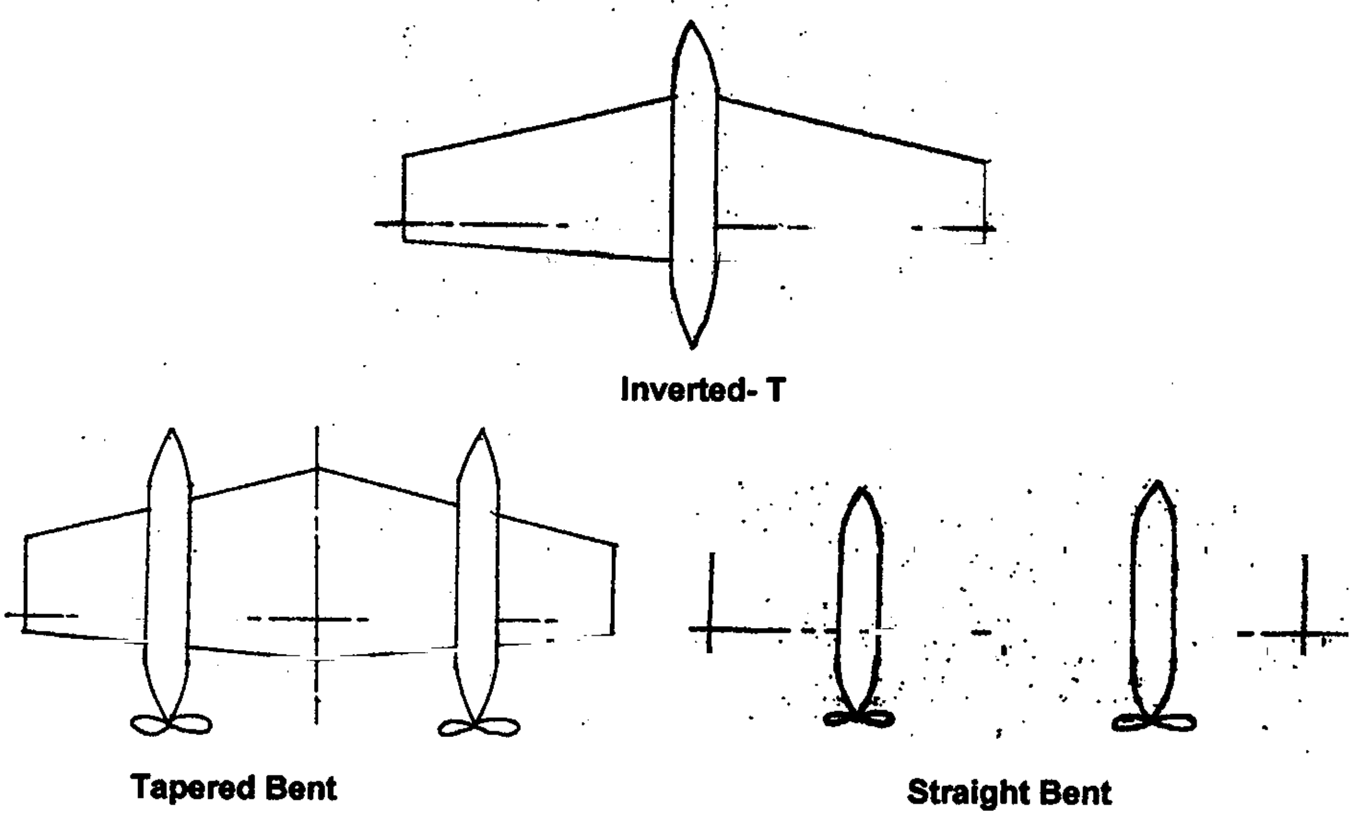


Figure 26. Most Common Foil Configurations

G. The final parameter we must determine is the thickness-to-chord ratio .The thinner the foil, the higher the cavitation speed (see Appendix B). However, the thinner the foil, the heavier the foil structure required . A thickness-to-chord ratio of .077 is about the maximum that is cavitation free at 50 knots for foil loadings from 800 to 1600 pounds per square foot.(see Appendix B)

The next final input to the cavitation study is the flight envelope. The basic steady state flight envelope is bounded by the maximum speed, the minimum speed, the maximum foil loading (maximum displacement), and the minimum foil loading (minimum displacement) A typical flight envelope for a hydrofoil with an average foil loading of 1500 pounds per square foot is shown in Figure 27. Section A of Figure 27 is bounded by the average foil loading. Foils, however, have an elliptical pressure distribution and the maximum local loading is about 15% above the average and about 12% below the average. Sections B, therefore are added to the average loading to get maximum and minimum local loadings on the foil. To take care of rough water and control forces, Sections C are added. The loadings in Section C are transient and if outside the cavitation bucket cause only intermittent and therefore less damaging cavitation.

By superimposing the flight envelope on the cavitation buckets we can ascertain how much cavitation, if any, we will encounter. This is done in Figure 28 for a 1500 pounds per square foot foil loading and for one with a 1400 pounds per square foot loading in Figure 29

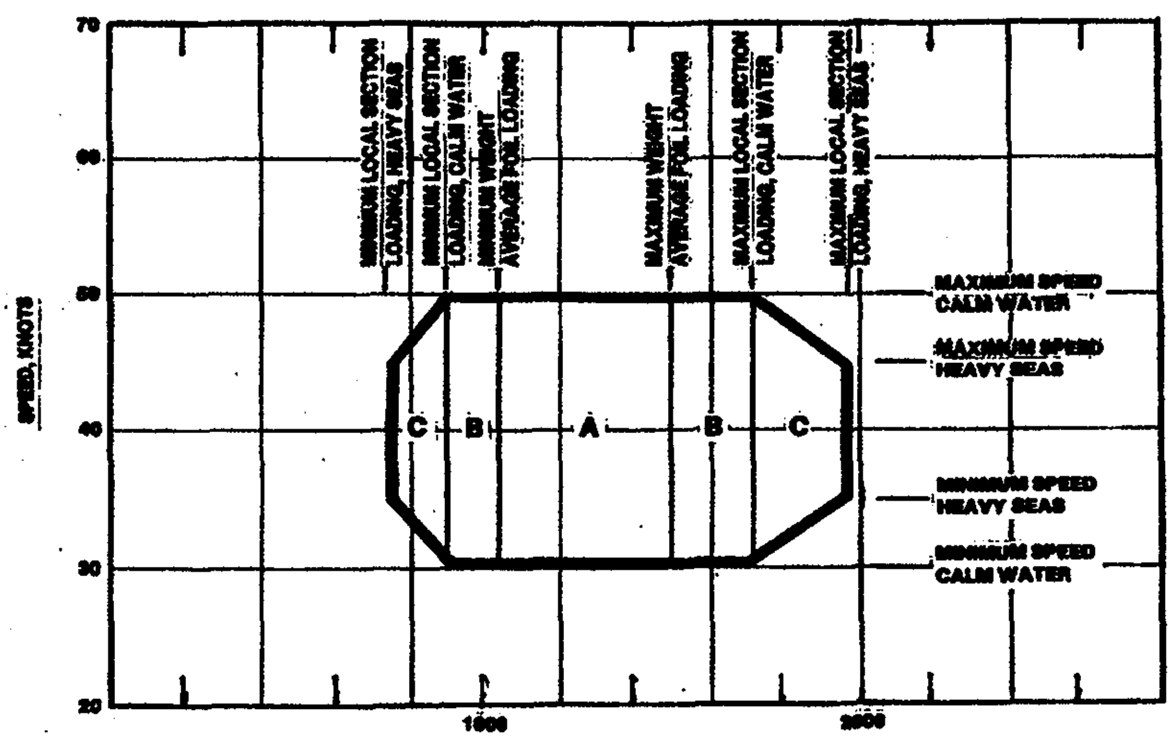


Figure 27. Flight Envelope

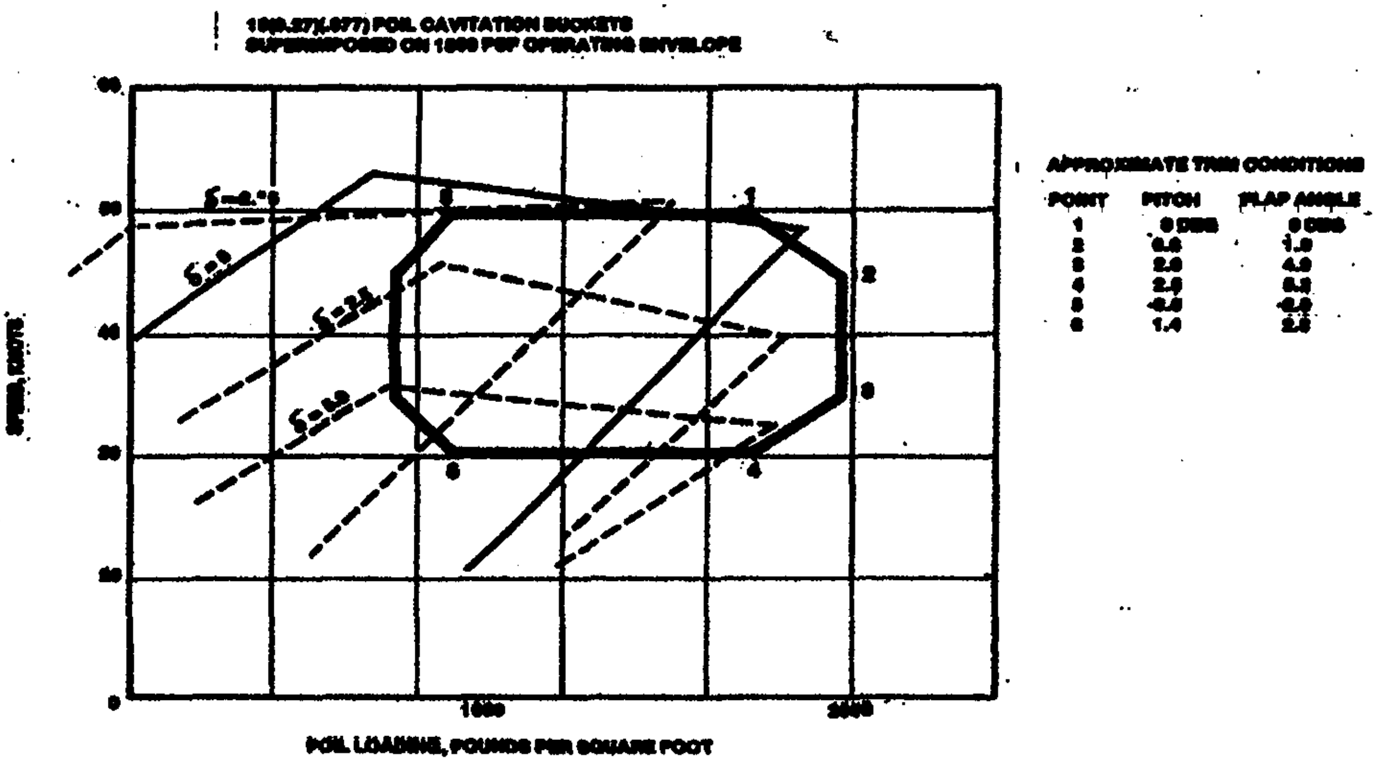
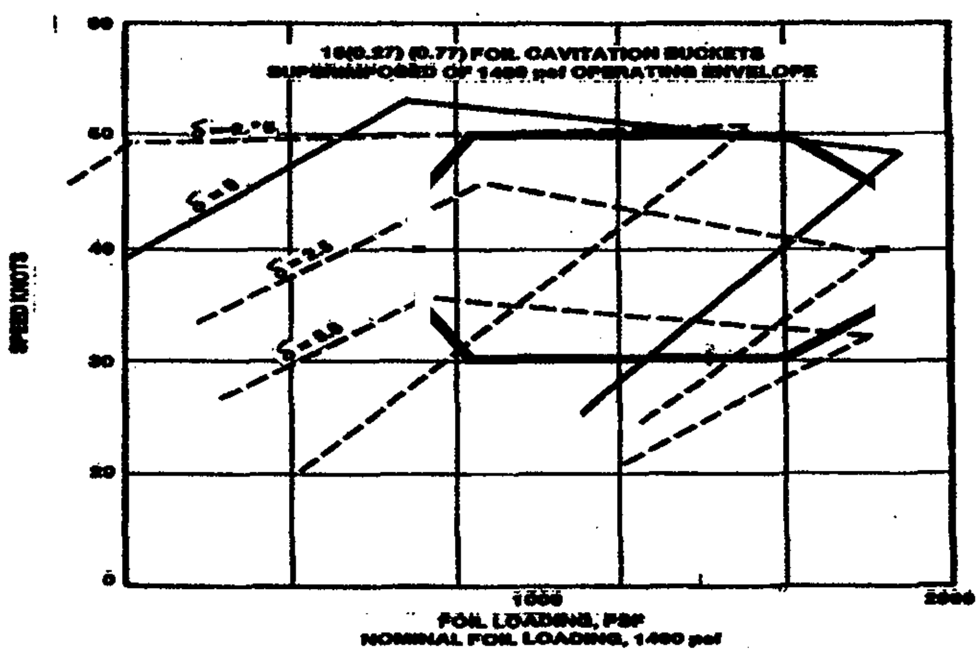


Figure 28. Flight Envelope Superimposed on Cavitation Bucket, 1500 psf



APPROXIMATE TRIM CONDITIONS

POINT	PITCH	FLAP ANGLE
1	0 DEG	0 DEG
2	0.8	1.0
3	2.0	4.0
4	2.5	5.2
5	-0.5	-2.0
6	1.4	2.8

The points of the flight envelop have the same number as those in Figure 28

Figure 29. Flight Envelope Superimposed on Cavitation Bucket, 1400 psf

29.(The buckets used are the ones for varying flap angles) The approximate trim conditions at the extremes of the flight envelope is shown to the right of each figure. As can be seen, with a foil loading of 1500 pounds per square foot, quite a bit of the flight envelope lies outside of the cavitation bucket but with a foil loading of 1400 pounds per square foot considerably less lies outside the bucket. Most of this cavitation occurs at high speed, maximum weight, and during maneuvering and in rough water which probably represents only a small portion of the foilborne hours. Whether this cavitation collapses off the foil surface or is the damaging type which collapses on the foil can be determined by model tests. If it is determined that the cavitation is intolerable, one probably should probably consider lowering the foil loading. This would, within the span restraints, increase the foil chords, foil weight, and decrease the aspect ratio, all of which are undesirable. Another approach would be to see if meeting the maximum speed at two-thirds fuel weight instead of full load displacement. would be acceptable to the customer.

If on the other hand the cavitation appears tolerable, one may want to consider raising the takeoff speed to 26 knots. This will allow you to increase the foil loading to 1514 pounds per square foot. This would result in a 8% decrease in foil area, a small increase in the aspect ratio of the aft foil, and also a decrease in foil weight, all desirable.

As can be seen, the design of a foil system is a multifaceted problem and this paper tries to show how the parameters interact with one another. At this point, however, a foil system design must be selected in order to proceed with sections on performance and control. An assessment of all the factors covered in this section plus previous experience demonstrates that the foil system selected in the following section is a well balanced and viable system design.

Performance.

Foil system

In order to proceed with the section on the performance of a hydrofoil, let us will select a foil .

Span	56	47
Aspect Ratio	5.03	5.54
Taper Ratio	3 to 1	3 to 1
Sweep	17.64 Degrees	16.31 Degrees
Thickness/Chord	0.077	0.077
Foil Loading	1400 psf	1500 pfs
Camber	0.3	0.3
Configuration	Bent Tapered	Inverted T
Lift Control	20% Triling Edge Flaps	20% Trailing Edge Flaps
Power Plants		
Foilbourne Propulsion	2 !5000 HP Gas Turbines	
Hullborne Propulsion	2 1250 HP Diesel Engines	
Auxiliary Power	800KW Diesel Generators	

Table 1. Hydrofoil Parameters Chosen to Assess Perform

based on our judgment from the many inputs we have just discussed in the previous section A viable foil system is one with the parameters. shown in Table 1.

Drag

The drag of a hydrofoil system is made up of parasite (frictional drag and spray drag) and drag due to lift (induced drag, separation drag and wave drag).Grumman's expressions for these drags are shown in Table 2. The calculated values for each component of a 675 -tonne ship doing 50 knots from the HANDE program and using Grumman's formula are also shown in Table2. As can be seen, the two methods agree very closely. If one has access to the HANDE program he would find it easier to use. The drag due to lift is the induced drag plus which Grumman calls the *wave and separation drag*. The induced drag coefficient can be obtained

Component	Parasitic drag Calculations Grumman's Formula Parasitic Drag	Speed 50 Knots Value from HANDE	 Grumman's
Foreward Foil	[1+1.2(t/c)][2.29Sff]qCfff	11035	10709
Foreward Strut	[1+1.2(t/c)aver] 1.2(Sfs)qCffs	4460	4645
Foreward Pod	[1+1.5(Dfp/Lfp)][3.2DfpLfp)]qCffp	1640	1560
Spray Drag	(0.24tsurf) (q)	1519	2173
	Total Foreward System	18654	19087
Aft Foil	[1+1.2(t/c)][2.25Saf]qCfaf	31212	29812
Aft Strut (2 req)	2[1+1.2(t/c)][1.2(Sas)qCfas	14994	18081
Aft Pod(2 req)	[1+1.5(Dap/Lap)][3.2DapLap]qCfap	9410	8835
Aft Spray	(.24tsurf) (q)	11352	12696
	Total Aft System	66968	67426
Air Drag	0.0006(frontal area)q	5121	5121
	Total Parasitic Drag at 50 Knots	90743	91634
Drag Due to Lift			
Front Foil	[Cdif+.10185C -.37825C +.00425]qsff	9737	10378
Aft Foil	[Cdia+.10185C -.37825C +..00425]qSaf	14605	15567
Total Ship Drag		115086	117579

Table 2. Hydrofoil Drag Calculations

Notes

1. C_{fff}, C_{ffs} and C_{ffp} are the friction coefficients of the forward foil, strut and pod respectively

2. C_{faf}, C_{fas} and C_{fap} are the friction coefficients of the aft foil, strut and pod respetively

3. L_{fp} and L_{ap} are the lengths of the fore and aft pod respectively

4. D_{fp} and D_{ap} are the diameters of the fore and aft pods respectively

5. The friction coefficient C_f for lengths of component of hydofoils below 1500 tonnes can be calculated very closely by the following expression, $C_f = .005158[\ LV\ ]^{-.13844}$, where L is the length in feet of the individual component, V is the ship speed in knots, and g is the acceleration of gravity in feet per second squared.

from Figure 25 and the *wave and separation drag* can be calculated Grumman's formula if HANDE is not available. As can be seen both methods for calculating drag due to lift give about the same values for drag. The drag calculated is for relatively clean foils. The parasitic drag of the foil system can increase up to 20% depending on the how dirty they are.

To find out how much fuel that a 675- tonne hydrofoil with a 60- tonne payload can carry it is necessary to get a weight breakdown of the ship. The weight breakdown of a 675 tonne hydrofoil from Reference 12 based on the HANDE program is shown in Table 3. This table shows that the ship can carry 187 tonnes of fuel of which 183 tonnes are available.

WEIGHT DATA In Tonnes	
Hull Structural weight	**105.3**
Propulsion System	**56.0**
Electrical System	**16.1**
Command and Control (group 400)	**43.1**
Auxiliary Systems	**45.3**
Foil and Struts	**83.1**
Outfit and Furnishings	**38.6**
Armament	**12.4**
Provisions	**60.0**
LIGHTSHIP	**459.8**
Crew and Effects	**5.3**
Missiles and Armament	**10.1**
Provisions	**4.0**
Fuel	**187.0**
Lube Oil	**1.7**
Fresh Water	**6.7**
Total Loads	**674.6**

Table 3. Weight Breakdown

The propulsion system will be assumed to be a pair of gas-turbine-driven propellers, one in each of the rear pods. The propulsive coefficient and specific fuel consumption used in Tables 4 and 5 are obtained from Figure 8. Table 4 shows the performance we can expect from our hydrofoil ship. As can be seen, the ship falls 133 nautical miles short of our specification. This is equivalent to a shortage of 13 tonnes of fuel. Being this close on the first try is unusual but shows the accuracy of Figure 20 and Reference 12. If, however, we fell short of our specification say by 220 nautical miles and our range factor was 10.2 nautical miles per tonne of fuel, this would be the equivalent of 22 tonnes of fuel. Our next iteration would start with a larger ship. The rule of thumb, again based on Reference 12, is to increase the displace-

displacement of the ship 3% for every 100 nautical miles of additional range. Therefore we would increase the displacement 6.6% or 45 tonnes for our next iteration.

Speed knots	Parasite Drag pounds	Drag Due to Lift pounds	Total Drag pounds	lift/drag ratio	Propulsive Coefficient	Power Horsepower	SFC Pounds/HpHr
50	90743	24342	115085	12.65	0.61	28968	0.400
45	73501	30917	104418	13.94	0.635	22724	0.430
40	58076	40500	98576	14.77	0.645	18773	0.442
35	44464	59780	104244	13.97	0.62	18072	0.445
30	32668	90843	123511	11.79	0.57	19963	0.440
25	22686	146793	169479	8.59	0.51	25512	0.428
Speed Knots	**Propulsion Pounds/hour**	**Auxiliary Pounds/Hour**	**Total Fuel Rate Pounds/hour**	**Range Factor Naut. Miles/Ton**	**Range Nautical Miles**	**Endurance Hours**	
50	11587	500	12087	9.27	1696	33.9	
45	9771	500	10271	9.81	1796	39.9	
40	8298	500	8798	10.18	1864	46.6	
35	8042	500	8542	9.18	1680	48.0	
30	8784	500	9284	7.24	1325	44.2	
25	10919	500	11419	4.90	897	35.9	

Table 4. Performance in Calm Water with Full Fuel Load

The range calculated in Table 4 is based on full load displacement, however, it is more reasonable to calculate the range with a two-thirds fuel load. This is done in Table 5 As can be seen using an average displacement with two thirds fuel load the required range is met.

Speed knots	Parasite Drag pounds	Drag Due to Lift pounds	Total Drag pounds	lift/drag ratio	Propulsive Coefficient	Power Horsepower	SFC Pounds/HpHr
50	90743	20388	111129	11.87	0.61	27973	0.4
45	73501	24310	97811	13.49	0.635	21286	0.430
40	58076	32110	90186	14.63	0.645	17175	0.442
35	44464	58274	102738	12.84	0.62	17810	0.445
30	32668	71890	104558	12.62	0.57	16899	0.440
25	22686	117229	139915	9.43	0.51	21082	0.428
Speed Knots	**Propulsion Fuel Rate**	**Auxiliary Pounds/hour**	**Total Fuel Rate Pounds /hour**	**Range Factor Naut. Miles /ton**	**Range Nautical Miles**	**Endurance Hours**	
Knots	**Pounds/hour**	**Pounds/Hour**	**Pounds/hour**	**Naut. Miles/Ton**	**Nautical Miles**	**Hours**	
50	12028	500	12528	8.94	1636	32.7	
45	9406	500	9906	10.17	1862	41.4	
40	7643	500	8143	11.00	2014	50.3	
35	7837	500	8337	9.40	1721	49.2	
30	7233	500	7733	8.69	1590	53.0	
25	9015	500	9515	5.89	1077	43.1	

Table 5. Performance in Calm Water at Two Thirds Fuel Load

Control

In concept design it is almost taken for granted that using modern control theory one can devise a control system which will both stabilize a hydrofoil and attenuate its motions in a seaway. This is for all practical purposes true, but a little thought in establishing the basic configuration of the ship can do a great deal in lessening the burden of the control designer. For example:

- Configuring the strut/foil system to give dynamic stability at all attitudes even with a strut ventilated 34

- Making the lift coefficient and the foil loading of the after foil lower than that of the forward foil to give some degree of inherent pitch stability.

- Adjusting the location of the struts and the depth of the forward foil system to minimize he effect of its downwash and tip vortex on the after system.

The key to developing a good control system is the ability to derive an accurate mathematical model of a hydrofoil ship. A good review of the equations of motion of a hydrofoil and the seaway for application in a simulation is given by Jamieson in Reference13. Through the years hydrofoil simulations have progressed from simple linear representation to rather sophisticated computer modes which include structural compliance and non-linear flow phenomena. These simulations are used to determine the control laws for the autopilot and of utmost importance is used to run failure mode analyses to assure within reason that the control system is designed to be fail safe. The simulation not only plays the dominant role in the design of the control system but also is an essential tool in the debugging of the ship by identifying problems and the source of any anomalous behavior during the shakedown of the ship. It also can be used to assess the effects on the stability and controllability of the ship in such operations as missile and torpedo launchings, gun firing, etc.

Reference 14 gives a history and an overview of hydrofoil control system development. It points out that the basic control system block diagrams of most submerged-foil hydrofoils are all but indistinguishable. Basically, the flying height of a hydrofoil is controlled by the forward foil, pitch by the after foil, and roll by differential control of the after foils. Turning is normally achieved by rolling the ship as a function of helm angle and rotating the forward foil system as a function of roll angle, (for an airplane configuration the rear strut is rotated as a function of roll angle).

Frequency-sensitive filters in the height and acceleration loops are designed to make the ship tend to contour the long (low frequency) waves and platform through short (high frequency) waves. For those that are interested in how these are implemented in a digital autopilot are directed to References 15 and 16. Reference 17 reviews the actual problems in installation, check out, and operation of such a system on the experimental hydrofoil AGEH. When reading these references one must take into account that this autopilot was designed in the 1970s when computers were slower and had limited memory. This necessitated programming in machine language using an octal arithmetic and floating point arithmetic, both cumbersome and prone to error.

At this point in this section I would like to do a quick overview of the control system developed in 1990s for the Norwegian ***Foilcat***. The advance in computer speed and memory capacity and drop in cost by 1993 allowed the use of three computers. This made it possible in case of a failure to detect which computer is at fault and can be removed from the system (in less than 40 milliseconds). It also allowed several sets of gains such as for calm water, low sea states , and high sea states. Although the ship was designed for sea state five (significant wave height of 10 feet). it was operated at 43 knots in a sea with significant wave height of 12 feet with measured rms vertical accelerations between 0.065 and 0.075g depending on the heading.. Tests were run to check the fail-safe features. The potentially worst failure would result in hard over control failure which would drive a flap hard over. In these tests each flap was driven hard over. The worst ship motion for a hard-over flap was 4 degree roll, and 3 degree pitch.

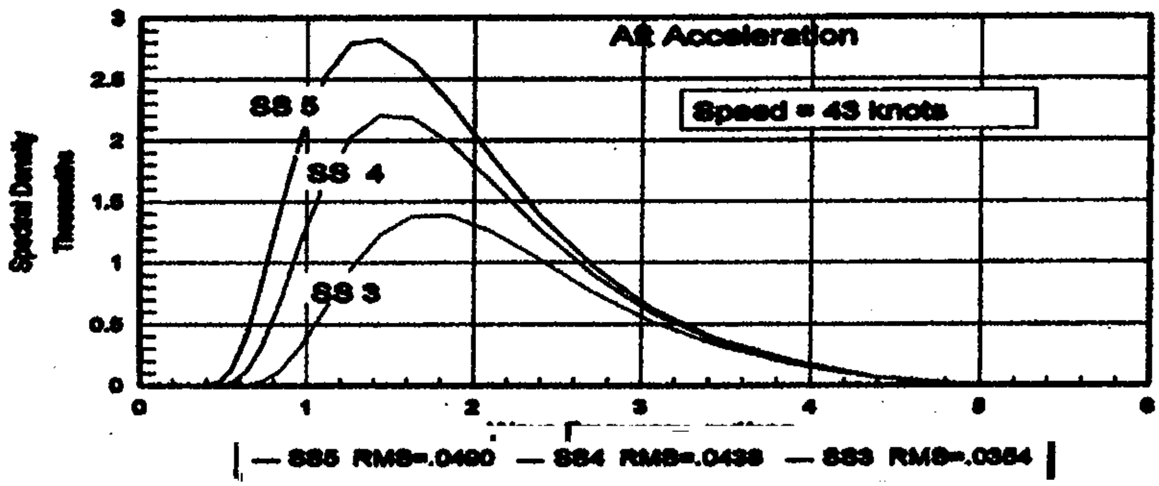


Figure 30. Simulation Motions of Foilcat, Gains Set for Heave Control Only

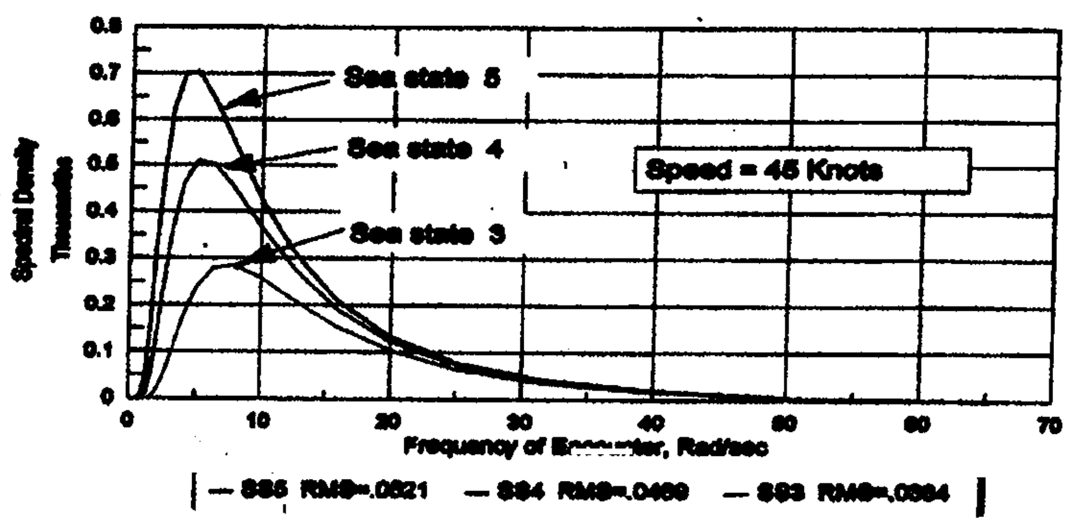


Figure 31. Simulated Accelerations of *Foilcat* in Various Seastates Gains Reduced by 33%

The basic concept of this control system is to control the motion at each strut by its inputs from its respective accelerometer, see Reference 18. As accelerometers and integration of their output is not perfect the ships height, pitch and roll would drift off. To prevent this sensors (height sensor, pitch, pitch rate, roll, and roll rate gyros) provide relatively low frequency feedback signals to maintain the ship's attitude. To check the ability of this control to control the motion of the ***Foilcat*** in a seaway, a simulation of the heave motion was made. Gains were set to give at least 2 to 1 gain margin and 60 degrees phase margin to assure good stability. The results are shown in Figures 30, and 31. The resulting rms accelerations shown in figure 30 are low, but this simulation there is no margin for roll or pitch feedbacks. In practice the nominal gains, therefore, were reduced by 33% and the results of this simulation are shown in Figure 31. The resulting rms acceleration at 45 knots in sea state 5 increases to .062g, which is in good agreement with sea trials.

One should note in figures 30 that the spectral density of acceleration for sea states 3, 4 and 5 are approximately the same for frequencies of encounter above 20 radians/second (3.18.Hertz). Since the frequency response of the control system of most hydrofoils is about 3 Hertz, it cannot attenuate the motion created by the spectral energy above 3 Hertz. That is why the small amplitude jiggle in sea states 3, 4,and 5 is always present, although it is not so noticeable in the higher sea states, as it is masked by the larger motions.

Summary

Although the basic concept of hydrofoils has been around for 85 years, it has only been in the last 35 years through advances in materials, light weight propulsion plants, and control theory, they have become a viable open ocean concept. This paper has tried to give an overview of the status. as of the early 1980's, of the various subsystems which make up a hydrofoil. By going through the foil design process, I have hoped to impress on the reader the close interrelationship of the many disciplines involved. The design of a hydrofoil demonstrates the very essence of engineering, that is the trade-off and compromise among often conflicting requirements of many disciplines to arrive at a good balanced design.

The introduction and acceptance of hydrofoils into fleets of the world has been painstakingly slow, but their unique attributes should assure them a place in the future. Unfortunately, most military hydrofoils have been retired. The surface-piercing commercial passenger hydrofoils have been largely replaced by catamarans. The fully-submerged commercial hydrofoils, except in the Pacific rim, are also being replaced by catamarans. Many of these catamarans have small controlled submerged foils forward which greatly reduces the pitch and roll motion. Maybe sometime in the near future the unique features of a fully-submerged hydrofoil will find a niche in high speed ships which need to operate in rough water, for where else can you get high speed, in high sea states in a relatively small size, all at the same time.

References

1. Ellsworth ,W.M. and O'Neill, W.C.
"The U.S. Navy Hydrofoil Development Program, A Status Report", Naval Research and Development Center Technical note SDD-OH50-62, Nov. 1970

2. Crew, P.R., "The Hydrofoil Boat: Its History and Future Prospects", Quarterly Transactions, The Institution of Naval Architects, Vol 100, No.4, Oct. 1958

3. Hayward, L., "The History of Hydrofoils", Series of articles published in Hovering Craft and Hydrofoils (Kalerghi Publications, London, England) Vol 5, 1966.

4. Baron Von Schertel's luncheon address " Experiences of a Pioneer Hydrofoil designer", AIAA Meeting, Annapolis Maryland, July 18, 1972.

5. Chen, Yoong, " Motions and Accelerations fo AGEH When Heave-to in Extreme Sea States" Stevens Institute of Technology Report, Aug 1963.

6. Shen, Y. Wermter R. " Recent Studies of Struts and Foils for High Speed Hydrofoils " , Marine Technology, Vol. 16, January, 1979.

7a. Besch, P.K. and Liu, Y-N, " Bending Flutter and Torsional Flutter of Flexible Hydrofoil Struts ", NSRDC Report 4012

7b. Besch, P.K. and Liu, Y-N. ,"Flutter and Divergence Characteristics of Four Low Mass Ratio Hydrofoils" ,NSRDC Report 3410.

7c. Besch , P.K. and Liu, Y-N., "Hydrofoil Flutter Analysis, Using a Moderated Strip Theory ", NSRDC 3624.

8.Sorenson, D. "AGEH Hydraulic System History and Evaluation Report ", Boeing Marine System H-7308-100-2239..

9. Bender, E., and Remington, P.," Hydrofoil Design For Minimum Power", B,H. Beranik and Newman Report 2511, 1973.

10. Hydrofoil Data Bank. A collection of most of the reports written by or for the Hydrofoil Development Project. These report are available on two CDs from the International Hydrofoil Society , P.O. Box 51 , Cabin John, Maryland , 20818 . or ordered from www.foils.org .

11. Brennan, A. ,Burroughs, J. , Wacker, D. " HANDE, a Tool for Integrating the Hydrofoil Preliminary Design Cycle." Paper given Oct. 1976 at SNAME, Pacific Northwest Section Salishan, Oregon.

12. Clark, D. J., O'Neill, W.C., Wight, D.C. " Balancing Mission Requirement and Hydrofoil Design Characteristics " AIAA/SNAME Advanced Marine Conference, April 1978, Paper 78-725

13. Jamieson, J. J. "Hydrofoil Simulation Equations Study- Mathematical Model Report" Volume I, II, III. Naval Training Devices Center Numbers TR-1630-2-1 ; 1630-2 ; 1630-3, Dec. 1966.

14. Johnston, R. J. and O'Neill, W. C. " the Development of Automatic Control Systems for Hydrofoil Craft." Presented at the International Hovercraft, Hydrofoil, and Advanced Transit System Conference, Brighton, England, May 1974.

15. Dogan, P., Decanio, F., Gamber, F., Medeiros, R. "Hydrofoil Universal Digital Autopilot (HUDAP), Phase 1,Final Report". Charles Stark Draper Laboratory Repot R-745, Jan. 1973

16. Gamber, F., Medeiros, R. "Hydrofoil Universal Autopilot (HUDAP) , Phase II, Final Report Charles Stark Draper Laboratory Report R-817, May 1974.

17. Coleman, J. ," Plainview (AGEH) Automatic Control System Evaluation" , Boeing Marine Systems H-7308-1000-2051.

18. O'Neill, William C. " The Maximum Attenuation of Seaway Induced Motions, Within a Given Set of Design Restraints, Possible for Hydrofoil Supported Ships." First International Conference on Fast Sea Transportation, Trondheim, Norway, June 1991

Additional References

The following documents were in the list of references in the original paper. They are listed here for those who would like to dig deeper into hydrofoil design and development.

19. Kaplan, P. "Use of Jet Flapped Hydrofoils as Ship's antipitching Fins" Oceanics report 6413.

20. DeYoung and Harper, "Theorectical Span Loading at Subsonic Speeds for Wings Having Arbitrary Planform" NACA Report 921, 1948

21 .DeYoung," Theorectical Span Loalding Due to Flap Deflection for Wings of Arbitrary Planform at Subsonic Speed" NACA Report 1071, 1952

22. Wright, R. "Flapped and Unflapped Foil Cavitation Characteristics, Technical Study Report Grumman Aerospace Corporation Report MAR-298-314-1, December 1979.

23. Wright, R. " Flapped Control of Incidence Hinge Moment and Foil Cavitation" Grumman Aerospace Corporation Hydrodynamic Note A6-18, 1973.

24. Abramson, H.N. , Wen-Hwa Chu, Irick, J.T. " Hydroelasticity with Special Reference to Hydrofoil Craft", NSRDC Report 2557, September 1967.

25. Besch, P.K., Rood, E. "A Parametric Survey of Hydrofoil Strut Flutter" DTNSRDC Report 76-0050, June 1976.

26. Casper, JjR, Yuan-ning Liu "Hydroelastic Analysis of the Grumman Design M 163(HYD-2) Inverted - Pi shaped Hydrofoil" DTNSRDC Report SAD-218E-1965, September 1978.

27. Yuan-ning Liu, "Considerations of Aeroelastic and Hydroelastic Effects on High Speed Ships" Presented at the Second Ship Structures Workshop at NSRDC 13-14, February 1973.

28. Ott, F.Wright,R. ," ASW Feasibility Study, Final Report" Grumman Aerospace Corporation Report Mar 298-812-1, February 1978.

29. Wislicenus, G.F. " Hydrodynamic Design Principals of Pumps and Ducting for Waterjet Propulsion" NSRDC Report 3990, June 1973.

30. Levy, J., Meggitt, D. " Study of Waterjet Propulsion for a 400 ton Hydrofoil Ship" Aerojet Electro System Company Report No.4366, October 1971.

APPENDIX A

DESCRIPTION OF *HANDE* PROGRAM

The HANDE program consists of four major sections as illustrated in Figure A-1. These can be called upon by the designer, interactively, to create and analyse a candidate ship configuration. A single ship configuration is available for evaluation within the program at any given time. This ship is referred to as the *CURRENT MODEL*.

A data bank provides a means of temporarily or permanently storing different *CURRENT MODELs* between analyses or between different computer sessions. The data bank also provides a source of data describing existing hydrofoil ships and ship components.

An *INITIALIZATION* section uses parametric methods to perform initial ship size and performance estimates. This module also provides a detailed estimate of ship internal space requirements as guidance for the designer in sizing the hull. The space required estimating technique used in HANDE is based on the surface ship space estimating relationships as defined in the Highly Sensitive Ship Synthesis Model for Surface Combatants developed by The Naval Ship Engineering Center (NAVSEC). These relationships have been modified to introduce mission duration sensitivity and be appropriate for hydrofoil ships up to 3500 tonnes.

The real power of HANDE is contained in the *SYNTHESIS* section of the program. *SYNTHESIS* consists of ten technology modules which use more detailed analytic methods to size major ship components. Figure A-2 illustrates the sequence of design through the *SYNTHESIS* section of HANDE. Two iterative loops are provided to ensure internally consistent designs. To provide a feel for the depth of analysis, a brief description of the technology modules is in order.

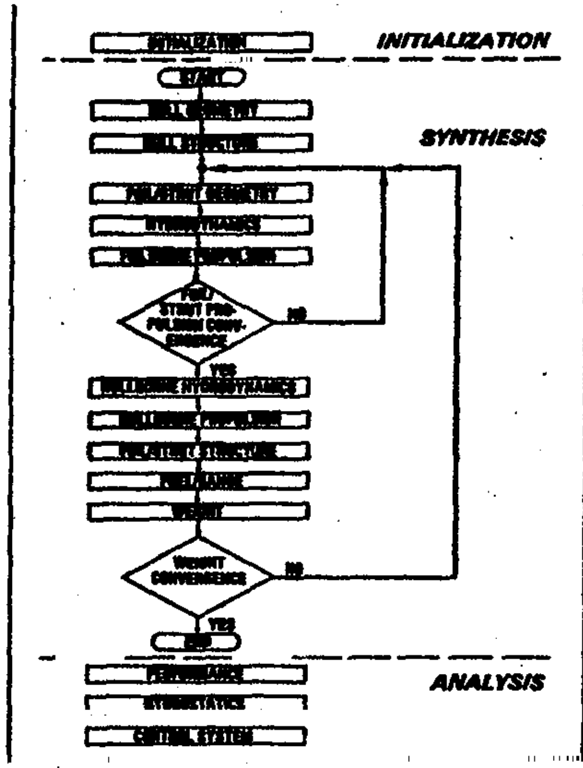


Fig. A-2 HANDE flow diagram.

Ship Geometry is handled by two *SYNTHESIS* modules. The Hull Geometry Module operates on user provided hull lines and warps these to define a new hull form which meets the physical characteristics requested by the designer. This module also

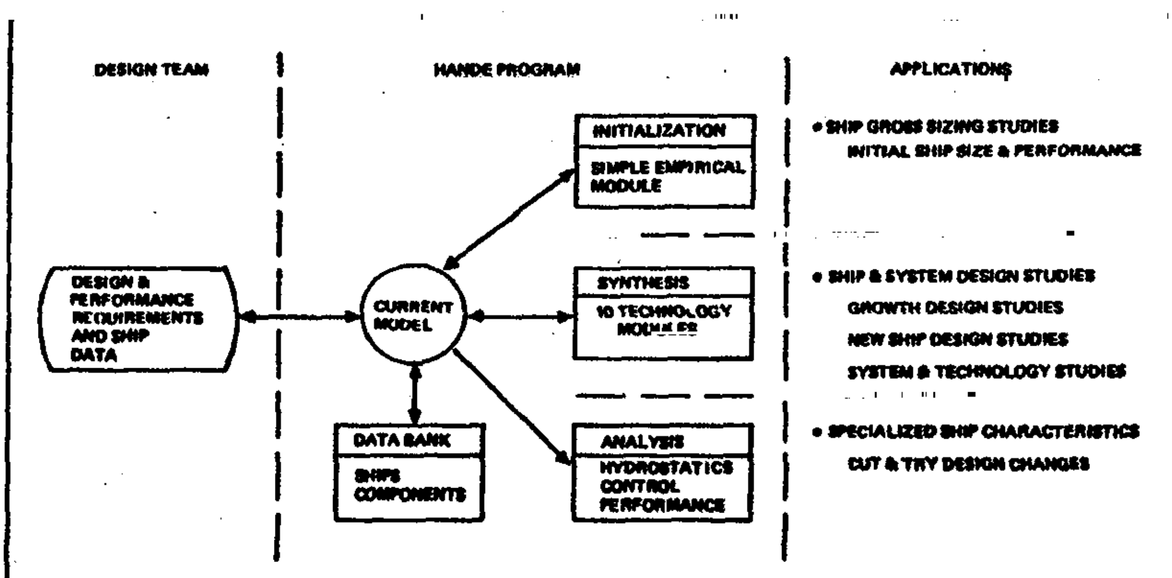


Fig. A-1 HANDE program structure.

defines geometric parameters for bulkheads, deck and girder locations, and superstructure size and location. The Foil/Strut Geometry Module sizes the foils, struts and pods in accordance with defined hull size and foil system configuration. Inverted T, Double inverted T, inverted π, U or three-strut configurations can be used for either forward or after foils.

The Structural Design in the HANDE program is performed by two modules. The Hull Structure Module calculates hull scantling data for hull elements defined in the Hull Geometry Module. These calculations are based on pressure loading data which may be calculated by this module or specified by the designer. Scantlings are calculated at three longitudinal positions for the hull bottom, hull sides and weather deck. Additional scantling information is calculated for lower decks, bulkheads, frames, girders, beams and stiffeners. The Foil/Strut Structure Module calculates the scantlings of the primary load carrying structure of the struts and foils. These calculations are based on the geometry data previously defined and on loading conditions derived from hydrodynamics and inertia forces developed during foilborne operations.

Hydrodynamic Calculations are performed in two modules. The Hydrodynamics Module calculates drag in the hullborne mode based on the hull and strut and foil geometry. Hullborne drags which are passed on to Hullborne Propulsion Module assume the foils to be in down position and their associated drags are included in sizing the hullborne plants.

Propulsion Calculations are handled by three modules within the *SYNTHESIS* section. The Foilborne Propulsion Module performs component sizing calculations for a foilborne waterjet or gear drive propeller propulsion system. The horsepower requirements for takeoff and maximum foilborne speed are based on the drag calculations received from the Hydrodynamics Module. The Hullborne Propulsion Module performs similar sizing calculations for separate or integrated hullborne propulsion plants using waterjets or propellers as propulsors. The Fuel/Range Module calculates fuel requirements for the propulsion plants, and the electrical and auxiliary power requirements in accordance with standard NAVSEC practices.

Weight Estimation is performed within the Weight Module which also calculates dynamic lift, and centers of gravity. Major emphasis is placed on those ship systems and components which are the largest weight contributors. Accordingly, the weight data is calculated to the following Ship Work Breakdown Structure (SWBS) levels:

SWBS 100 – Hull Structure Weight	3rd Level
SWBS 100 – Foilborne Propulsion Plant	4th Level
SWBS 200 – Hullborne Propulsion Plant	4th Level
SWBS 300 – Electric Plant	1st Level
SWBS 400 – Command and Surveillance	Input
SWBS 500 – Auxiliary System (– SWBS 567)	1st Level
SWBS 567 – Strut and Foil System	5th Level
SWBS 600 – Outfit and Furnishings	1st Level
SWBS 700 – [illegible]	Input
SWBS 700 – Loads	2nd Level or input

First level estimates for electrical plant, auxiliary system and outfit and furnishing weights are parametrically derived and further described in Appendix B.

The *ANALYSIS* section of HANDE is designed to provide additional information on the ship designs generated in the SYNTHESIS section for the designer's evaluation. These modules rely on the designer's judgement and experience for decisions too complex for the program to make automatically. The Hydrostatic Analysis Module allows the designer to determine the hydrostatic and stability characteristics of the ship. The Control Analysis Module analyzes the dynamic stability and controllability of the ship in a sea state. The Performance Analysis module permits the effects of sea state, fouling, off-design speed and fuel burn-off to be estimated. If the examination of the results of the *ANALYSIS* modules reveals a requirement to modify the ship, the designer usually has numerous alternatives. He then must decide on his course of action, modify the current model and rerun the design through the *SYNTHESIS* modules.

The modular structure and executive program of HANDE simplifies updating the state-of-the-art and expanding its capability. Currently, interactive graphics and the option to provide design data in metric or English units are being added.

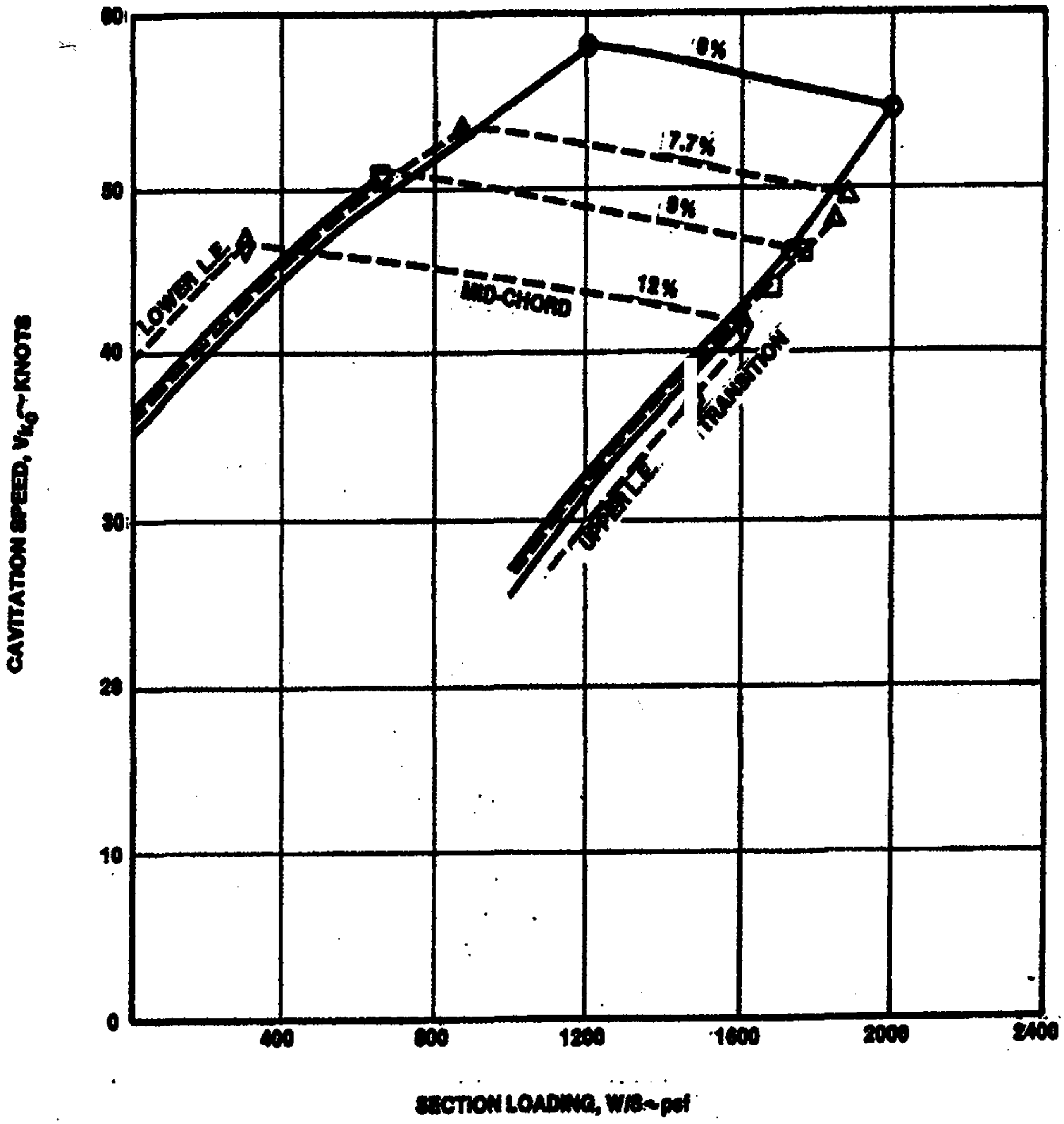


Figure B-1. Effect of Thickness-to-Chord Ratio on Cavitation (3 Feet Submergence)

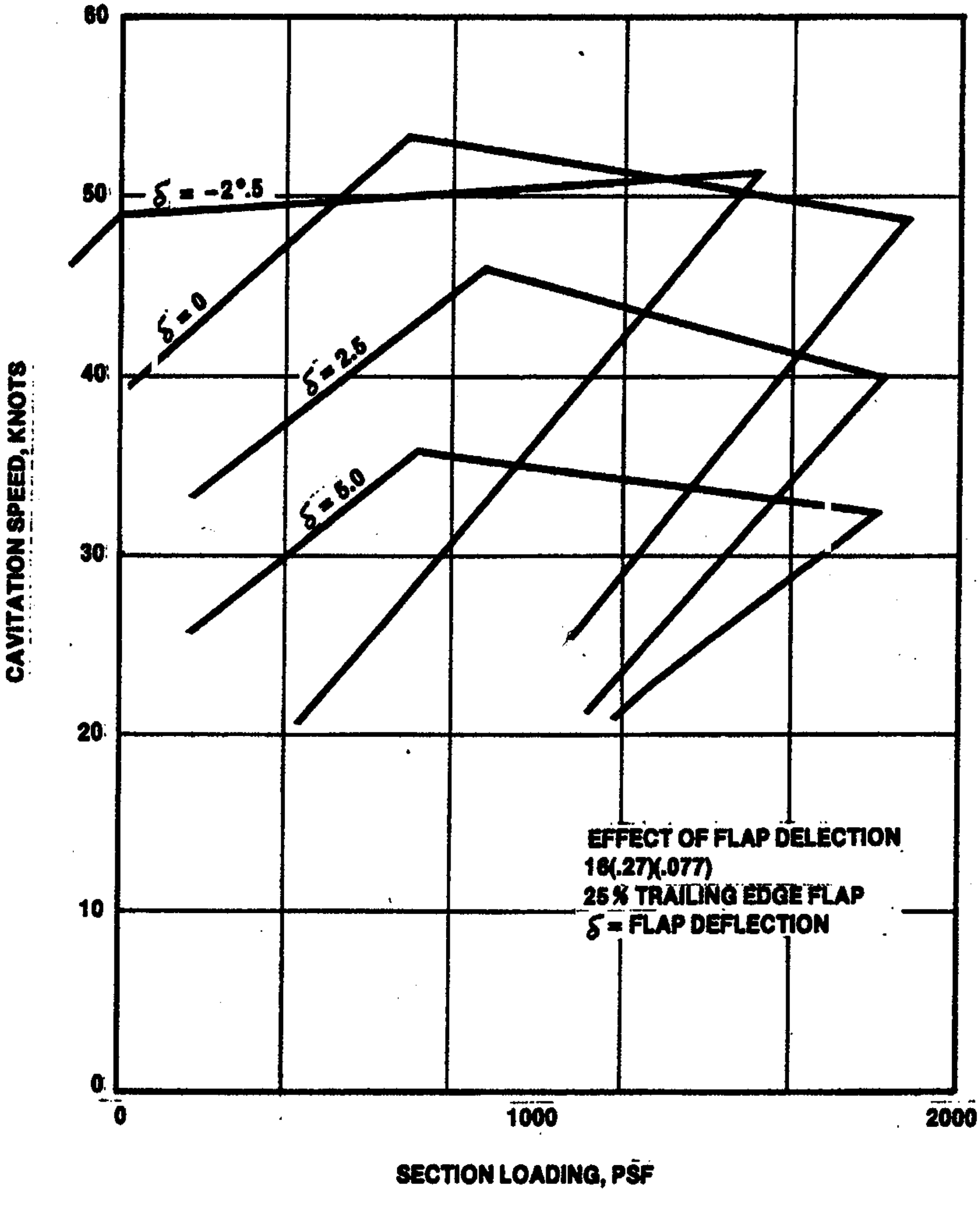
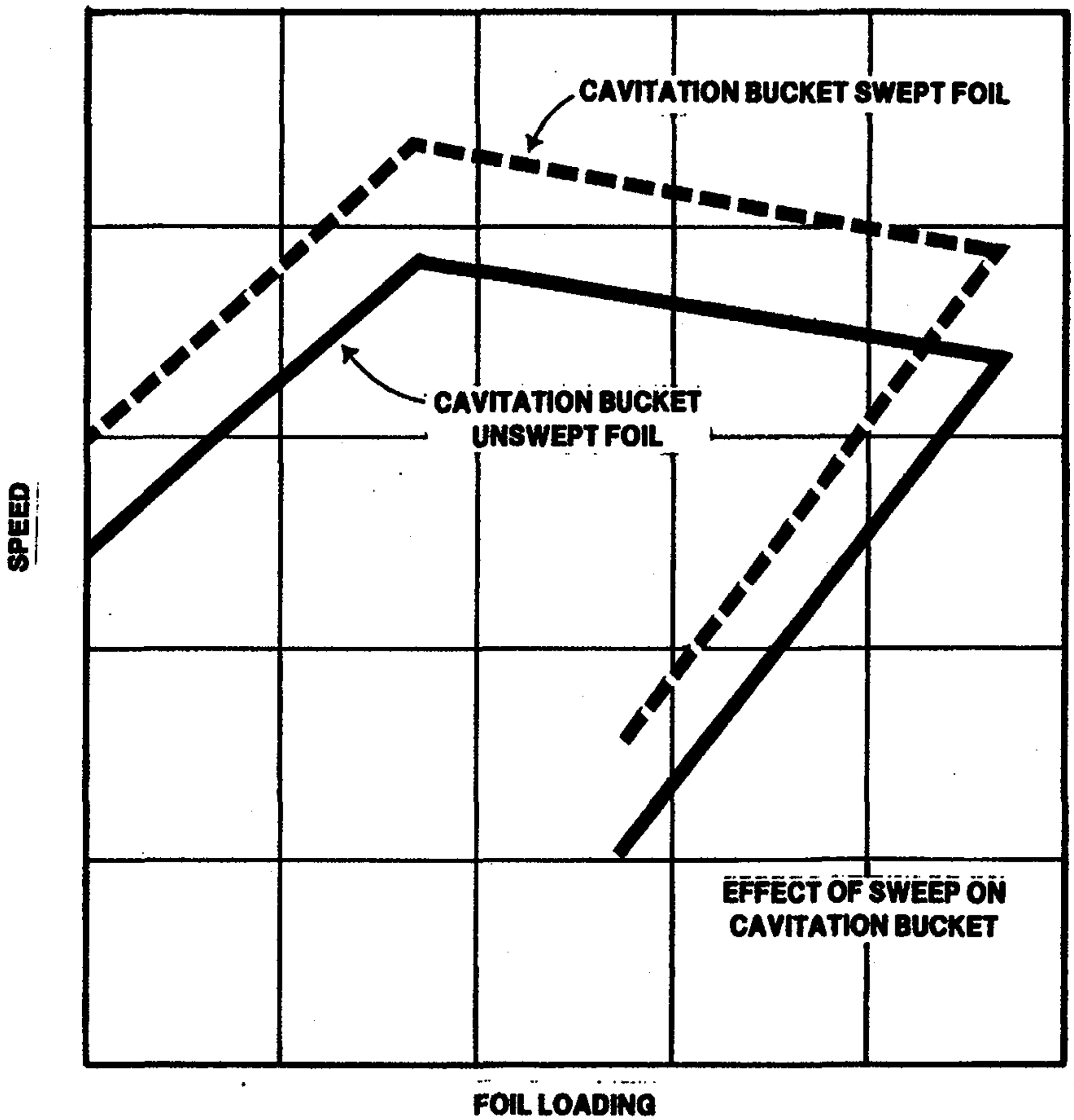


Figure B-2. Effect of Flap Deflection on Cavitation

Figure B-3. Effect of Sweep on Cavitation



This figure is included only to show the trend of sweeping foil on the cavitation bucket

Figure B-4 . Effect of Camber on Cavitation