HYDROFOIL DEVELOPMENT AND APPLICATIONS

BY

John R. Meyer and James R. Wilkins, Jr.

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ABSTRACT

This paper briefly describes the historical development and use of hydrofoil ships and craft in various countries, emphasizing the primary technical differences in the configuration of hydrofoil systems. The information herein has been extracted from various sources, which run the gamut from professional papers written by some of the principals mentioned to articles in various periodicals. It is presented as an aid to those who are not already familiar with the history of hydrofoil development, as well as to evoke hopefully pleasant memories for those who have participated in one way or another in the process. This is followed by current hydrofoil developments, possible future designs and technical aspects of hydrofoils.

INTRODUCTION

The basic principle of the hydrofoil concept is simply to lift a ship's hull out of the water and dynamically support it on wing-like lifting surfaces, i.e, hydrofoils, in order to reduce the effect of waves on the ship and to reduce the power required to attain modestly high speeds. Engineers and naval architects have been intrigued with the possibilities envisioned by this concept for many years. A United States patent for a hydrofoil was defined in the late 1880s, about the same time as the early airplane and airfoil patents. The earliest record of a successful hydrofoil flight is 1894 when the Meacham brothers demonstrated their 14 foot test craft at Chicago, Illinois. This compares with the Wright brother's first airplane flight in 1903. The early attempts to exploit the hydrofoil concept were frustrated by lack of suitable structural materials and power plants. However, advancement in these areas, much of it stemming from aircraft developments, have permitted development over the past 30 to 40 years of the technology necessary to achieve and demonstrate reliable and effective hydrofoil ships for both military and commercial applications.

Streamlined shapes, constructed of wood or metal, have been used for centuries to develop forces in water. Oars, rudders and even propellers have evolved from flat plates to streamlined cross-sections for improved performance. Likewise, fins used to provide roll stabilization use exactly the same theoretical concepts for developing forces. The uniqueness of hydrofoils is not, therefore, in how the forces are generated, but in how they are used; i.e., to replace, in part or in whole, the buoyancy forces for keeping the ship upright. In a true hydrofoil, as stated above, the intent is to raise the entire hull above the water's surface. Although the element of speed provided the original motivation for the development of hydrofoil ships, the vastly improved seakeeping of hydrofoils - particularly of those using submerged foils and automatic controls - are considered even more important for many applications. It is interesting to note that many of the most recent applications of the use of lift-generating foil surfaces are hybrids. The foils provide only a part of the lift necessary to raise the hull out of the water, and are used to greatly enhance the ride quality of the craft.

It is appropriate occasionally to recall the history of the development of these fascinating ships, not just because it is so interesting to see how difficult it has been to get to where we are, but because it sometimes leads us to realize that our focus needs to be sharpened if we are to continue to match the developmental strides achieved by our predecessors. The development of hydrofoil craft and ships, like many other creative efforts, seems to have proceeded in a very uneven fashion, with great interest and progress being made for a while, and then a period of little further advance. These periods of non-progress were usually due to some basic technical difficulty which could not be overcome until advancements were achieved in some other field. The major difficulty with which we appear to be dealing today is in the economical competitiveness with other types of craft for similar service. However, before addressing current developments, possible future designs and technical aspects of hydrofoils, it is appropriate to recount some history of hydrofoil development. The technical details of the craft mentioned in the Historical Perspective are explained in greater detail in the section entitled "Technical Aspects of Hydrofoils".

The compilation of the hydrofoil material in this paper would not have been possible without the resources of many fellow "Hydrofoilers", too numerous to mention. The authors were fortunate in having hydrofoil pictures and illustrations available from many sources. Credit is given to the U.S. Navy, U.S. Coast Guard, the Boeing Company, Fast Ferry International and Jane's High-Speed Marine Craft publications.

HISTORICAL PERSPECTIVE

Pre-World War II

One of the earliest successful attempts to use hydrofoils was accomplished by Enrico Forlanini on Lake Maggiore in 1906. Forlanini was interested in airships, aircraft and helicopters, and obtained a number of patents on his ideas and designs, most of which involved seaplane applications. Knowing that lift is proportional to the square of speed, but that the weight of the craft is relatively constant, he combined several foil shaped lengths mounted in parallel one over the other, like the rungs of a ladder. With this combination, as the speed of the craft increased, the lift increased. When the lift force thus created was greater than the weight of the craft, the craft would tend to rise up out of the water. The uppermost foil section would ultimately rise above the surface, decreasing the total lift being generated. By decreasing the amount of foil area immersed as the speed of the craft was increased, Forlanini could achieve stable operating conditions at a variety of speeds. With this arrangement he achieved a speed of just under 42.5 mph with a 60 hp engine driving coaxial airscrews on a boat that weighed about 2650 lbs. Note that these tests were conducted in very smooth water on a lake.

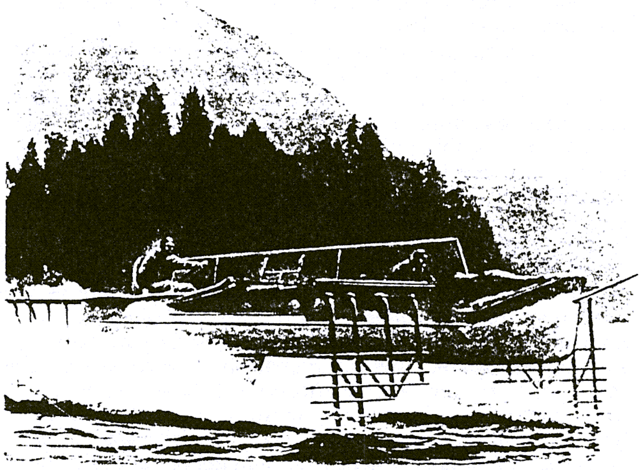


Figure 1 - Forlanini's Hydrofoil in 1906

Guidoni, another Italian researcher, varied the ladder foil concept by mounting the parallel lengths of foil at an angle to the surface of the water, in a dihedral arrangement, based on a concept which had been tried earlier by Croco. By this means, once the hull was out of the water, the immersed foil area at any speed ideally would be just sufficient to develop the lift necessary to equal the weight of the craft. According to Hayward, Guidoni's dihedral ladder foil configuration is credited with achieving the first successful take-off and landing of a hydrofoil seaplane in 1911.

Alexander Graham Bell's interest in hydrofoils was also kindled during this same time period. Bell's work with hydrofoils, like Forlanini's, sprang from an interest in seaplanes. Bell was concerned with the possibility of taking off and landing on water, which he considered safer than doing so on land. In *1908* he began to experiment with foil sections developed empirically with colleagues Baldwin and Rhodes. His experiments with small scale models and full scale craft continued for about 5 years. In 1911, Bell and Baldwin undertook a world tour which included a visit with Forlanini, where they witnessed tests on his hydrofoil on Lake Maggiore. It is understood that Bell purchased some of Forlanini's patents. Bell's work culminated in a craft designated the HD-4, with which he set a world speed record of 114 km/h (70.85 mph) in 1919.

Like Forlanini's craft, Bell's also used air propellers for propulsion. The most significant design features were three main sets of foil ladders, two forward and one aft, which provided lift. The aft ladder was steerable and was used as a rudder. A smaller fourth ladder fail was mounted at the bow to control pitching, and there were a series of airfoils mounted on top of the craft to provide added damping in choppy water. This latter idea was originally proposed by Forlanini.

Baldwin and Rhodes continued development of hydrofoil craft, producing several hydrofoil pleasure craft between 1918 and 1939. During this period they continually sought to interest the U.S. Navy in the military applications of hydrofoils, without success.

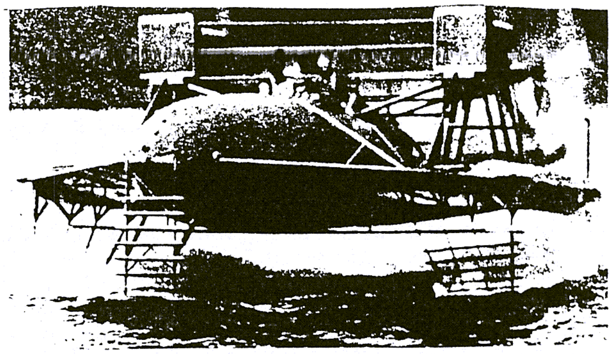


Figure 2 - Bell-Baldwin Hydrofoil HD-4

In Germany, in 1927, Baron Hanns von Schertel began to experiment with hydrofoil craft. He experimented with many different foil configurations, originally concentrating on fully submerged foils, but efforts to vary the lift of such foils when necessary were not successful. He finally reverted to experimenting with surface-piercing foil configurations and developed V-shaped foils. This shape provides the inherently variable lift generating characteristic needed for maintaining a given height above the water's surface. This is the simplest, and least expensive method available for height control - at least in smooth water. The problem with surface piercing foil systems in general, is that they are "surface followers" tending to stay at the same depth as long as the speed of the craft remains the same. This is ideal in smooth water, such as one may find frequently on lakes and on rivers. But when the surface height varies - such as when there are waves - a tendency for the craft to follow the shape of the waves will result in a very uncomfortably "bumpy" ride. Nevertheless, the surface height of rivers and lakes in most weather conditions is smooth enough to permit comfortable rides with surface piercing foils.

Thus, in 1935 Baron von Schertel was able to achieve success using V-shaped foils fore and aft on a test craft which incorporated all of the knowledge that had been acquired by several prior test craft. Propulsion was provided with propellers in the water. With only 50 hp, this craft successfully carried seven people at a speed of nearly 30 knots on the Rhine river, demonstrating for the first time the feasibility of fast, seaworthy transportation using the hydrofoil principle. These tests attracted much interest, including by the military, and brought about the partnership between Baron von Schertel and Gotthard Sachsenberg, with his shipbuilding organization.

In 1937 Gebruder Sachsenberg A.G. received, from the Cologne-Dusseldorf Steamship Co., the world's first order for a commercial hydrofoil boat, after a demonstration trip on the Rhine from Mainz to Cologne. To be on the safe side, the Schertel Sachsenberg syndicate built a larger test boat. This boat was completed just at the outbreak of WWII, which prevented the fulfillment of the original order.

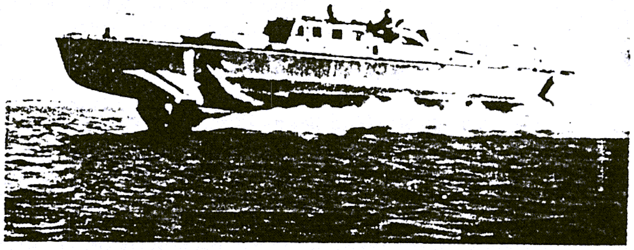


Figure 3 - Schertel-Sachsenberg Hydrofoil VS-6

Thus, by the late 1930s, the ability to operate hydrofoils in relatively calm water, with various configurations of surface-piercing foil systems, had been successfully demonstrated and a commercial application had been identified .

World War II apparently stopped all experimentation with hydrofoils except in Germany. There, however, the German Navy maintained its interest and supported the development of a series of test craft intended for various military missions. In addition to Baron von Schertel, Prof. Georg Weinblum and Dr. Otto Tietjens were among those who were involved in the design of these craft. Craft up to 150 feet in length, weighing up to 80 tons were built and successfully operated, although the larger craft were limited in performance by the size of the engines that were made available to the naval research program for testing. Other, smaller, craft attained speeds up to 55 knots, thus demonstrating the speed potential of hydrofoils.

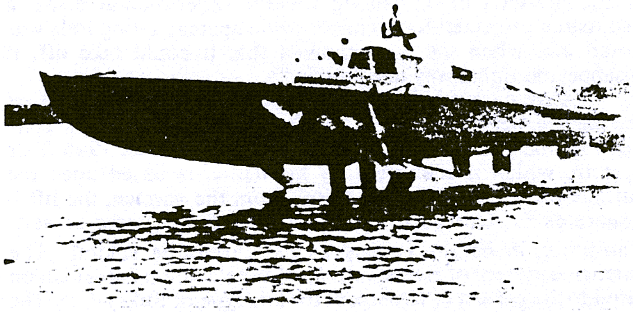


Figure 4 - Tietjens Hydrofoil VS-7

Post World War II

After WWII the interest in hydrofoil development was greatly increased, based largely upon the realization of how successful the German efforts had been. Many of the scientists who had been involved in the German hydrofoil developments participated in the initial post-war research and development efforts in the U.S. and in Russia. The 1950s were, in general, a period of broad investigation into all of the areas of interest to hydrofoil development, which were followed by years of building ever larger useful commercial and military vehicles. It is interesting to see how these developments occurred in various countries.

Switzerland and Italy

1950 - 1960 Because of limitations imposed on development of boats with speeds greater than 10 knots within Germany at this time, Baron von Schertel and his partner Sachsenberg moved to Switzerland, where, in 1952, they first produced the PT-10. This 7-ton craft had 32 seats and was capable of speeds up to 35 knots. It used fixed V-shaped surface piercing foils port and starboard, forward, and submerged foils aft. On 29 May 1952, Supramar, AG, based in Lucerne, was formed. That same year the PT-10 began the world s first hydrofoil passenger service on Lake Maggiore.

In 1954, Supramar awarded their first license to build craft of their design to the Leopoldo Rodriguez shipyard in Messina, Italy. In 1955, Rodriguez started production of the PT-20, a 32 ton, 72 passenger ship with a cruise speed of 35 knots. The foils were a standard Schertel-Sachsenberg surface-piercing type fore and aft, with slightly more than half of the weight carried on the bow foil. The angle of incidence of the bow foil could be manually adjusted within narrow limits from the helm position. This was the first hydrofoil craft to be built to satisfy maritime regulations, and became the first passenger hydrofoil to receive class certification. The success of these ships in coastal waters as well as inland waters led to the development of larger and larger versions; the PT-50, the PT-75 and the PT-100.

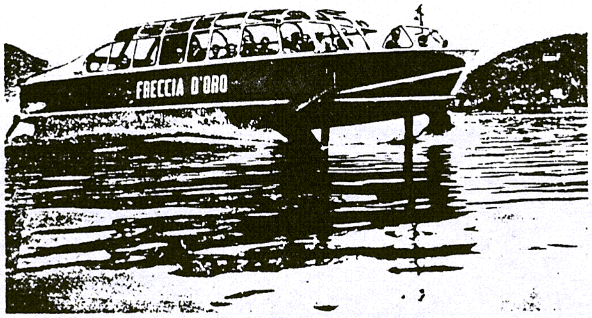


Figure 5 - PT-10 Hydrofoil

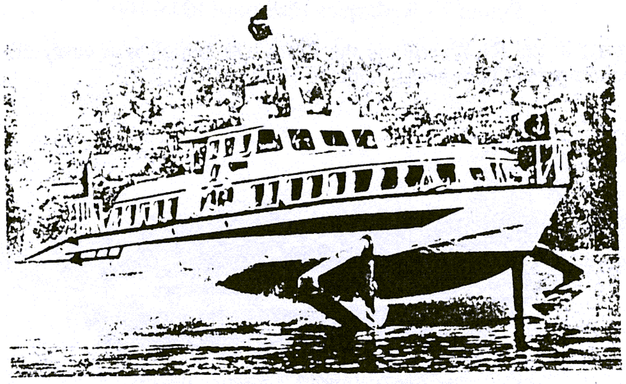


Figure 6 - PT-20 Hydrofoil

1960 - 1970 The PT-150 was the next major Supramar design. It had a displacement of 165 tons, was 124 feet in length, and carried 250 passengers. The foil system departed from previous designs in several ways. The forward foils were essentially unchanged in concept, being V-shaped surface-piercing foils of the standard Schertel-Sachsenberg variety. The after foil, however, was a fully-submerged foil, with two types of control. The angle of attack could be manually controlled hydraulically, giving the operator greater trim and lift control. In addition, the lift of the after foil could be varied by feeding air to the upper surface of the foil through small holes in the foil's upper surface. By feeding air into the flow above the foil, the lift generated by the foil could be reduced. The amount of air fed into the fluid was controlled by valves which were themselves controlled by signals from a damped pendulum and rate gyro. This system had been proposed to other hydrofoil designers, but has never found acceptance elsewhere.

1970 - 1992 In 1971, Rodriguez undertook production of their own craft, which were designated the RHS series. The first of these, the RHS-70, carried 71 passengers. The ships of this class displaced 32 tons and were designed for coastal routes. The foil system used surface-piercing foils fore and aft in an airplane configuration, but some relatively slight degree of adjustment could be made to the forward foil angle to adjust trim for varying load and sea conditions. In response to the increasing demand for commercial applications of hydrofoils for passenger service in routes that involved operation in rough water, Rodriquez and Di Blasi developed larger and larger craft in this series.

The RHS-110 carried 110 passengers up to 300 miles at a cruising speed of 37 knots. The foils of this 54-ton ship utilized flaps, which were controlled by an autopilot system to damp the ships motions in rough water conditions. The RHS-140 was slightly larger, but otherwise similar to the RHS-110. The RHS-160 incorporated a modification to the forward foils, which featured a W-shape when viewed from the bow. The

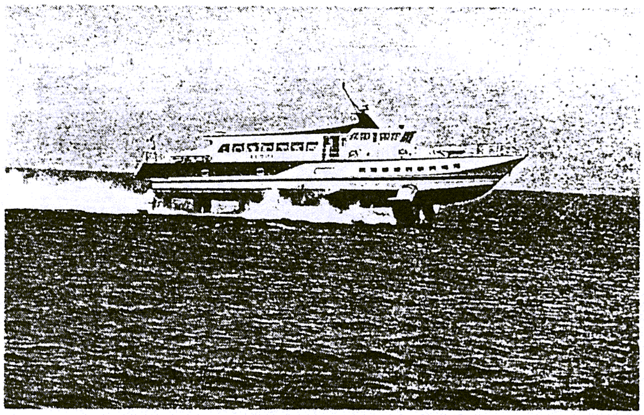


Figure 7 - Rodriquez Hydrofoil RHS-160

latest in the RHS series is the RHS-200, which will carry 200 passengers. These ships displace 120 tons.

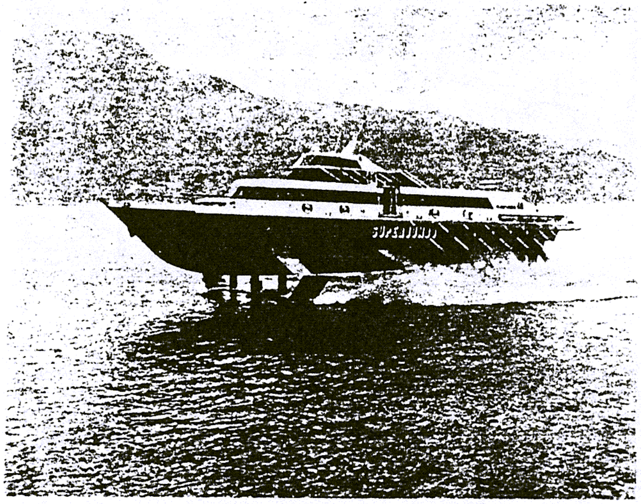


Figure 8 - RHS-200

The Italian Navy, having observed the performance of the U.S. Navy's TUCUMCARI, PGH-2, (described later) awarded a contract for the design and construction of similarly configured fast-attack craft. This ship, the SPARVIERO, at 60 tons displacement, carried missile launchers and a 76mm gun, but its mission scenario did not require extended foilborne operations. The SPARVIERO was followed by the NIBBIO class, which is similar to its predecessor in most ways, but its performance has been improved by modifications to the propulsion system.

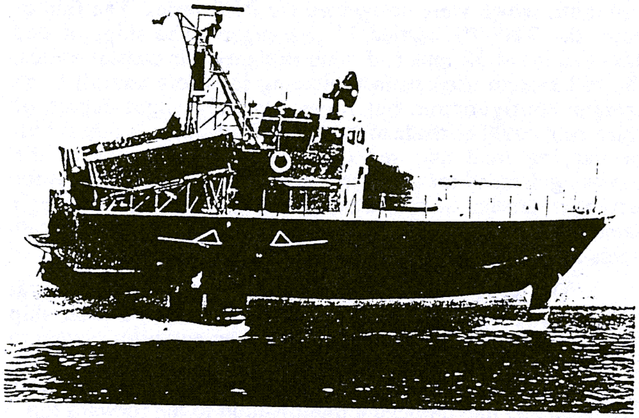


Figure 9 - SPARVIERO Class Hydrofoil, SWORDFISH

USSR

1950 - 1960 The Soviet government, perhaps because of the research work which they had carried out by themselves, were quick to avail themselves of the knowledge and experience of the Germans. The following description was provided by Baron von Schertel: "Immediately after World War II, the Russians established a design office in the Sachsenberg Shipyard, Dessau-Roslau, where the German military hydrofoils had been built. They engaged the available engineers and scientists who had been involved in hydrofoil technology, in addition to engineers from the former Junkers Aircraft Company, for accumulating knowhow. First, a hydrodynamic theory of submergence came to the knowledge of the Soviet engineers by the experimental work of the first person who used it - Wankel. The next step for the design office was to design and construct a 57-ton Torpedo hydrofoil vessel projected for 55 knots and powered by two Mercedes Diesel engines of 1,000 hp each. After completing a short, successful trial, the vessel was shipped to the Soviet Union. Among several experimental boats, a catamaran projected for 80 knots with supercavitating foils was noted and when the boat showed that it could take off, it disappeared right away into Russia."

Perhaps partly because of the information obtained from the Sachsenberg team, Dr. R.Y. Alexeyev developed a shallow-draft submerged foil system starting near the end of 1945. This system, which is identified by his name, is based upon the surface-effect principle. As a foil nears the surface, the lift it generates is decreased. Thus, such a foil system is self-stabilizing in height as long as the surface is smooth. The extensive system of rivers, lakes and canals in the Soviet Union provide the perfect environment for this type of foil system. The Alexeyev system used two main horizontal foil surfaces, one forward and one aft, with little or no dihedral, each carrying about one half the weight of the craft. Take-off assistance is provided by planing subfoils of small aspect ratio that are located in the area of the forward struts. These planing sub-foils assist in keeping the forward foil within a chord-length of the surface.

In the same year, 1957, the prototype RAKETA was launched. The success of this passenger vessel, 88 feet in length, displacing 27 tons and equipped with the Alexeyev foil system, has been enormous. By the early 1970s, more than 300 of these craft, in various configurations providing passenger capacity from about 60 to about 100, were operating on the Soviet Union's waterways.

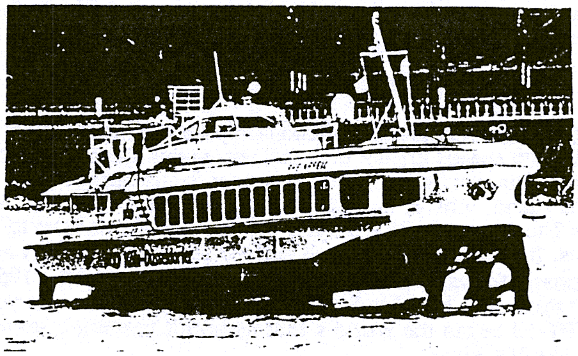


Figure 10 - RAKETA

1960-1970 As in Germany and Italy, the 1960s saw extensions of these proven designs to ever larger craft. METEOR, which was about twice the displacement of RAKETA and carried 116 passengers, was introduced in 1960. KOMETA, derived from the METEOR, was fitted with a completely revised foil system for its role as the first seagoing commercial hydrofoil built in the Soviet Union. This design used an auxiliary stabilizer foil to augment the surface-piercing foil forward. In addition to the surface piercing foil located aft, there is another auxiliary submerged foil located near the longitudinal center of grävity, to assist takeoff. These modifications permit METEOR to operate foilborne in waves up to nearly two meters high.

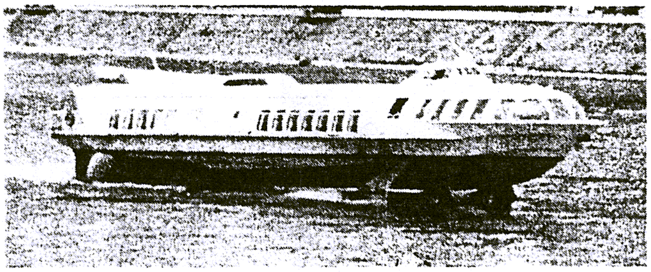


Figure 11 - METEOR

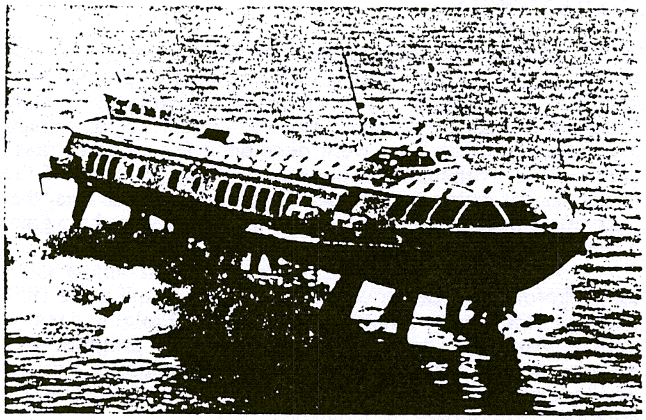


Figure 12 - KOMETA

The SPUTNIK, built for service in inland waterways only, displaced about 100 tons and carried 300 passengers. VIKHIR, a sea-going version of SPUTNIK, was introduced in 1962. The foil system of this ship was modified by giving the forward foils a sweepback of about 30 degrees, which provided some stability augmentation when operating in waves larger than those normally experienced by SPUTNIK.

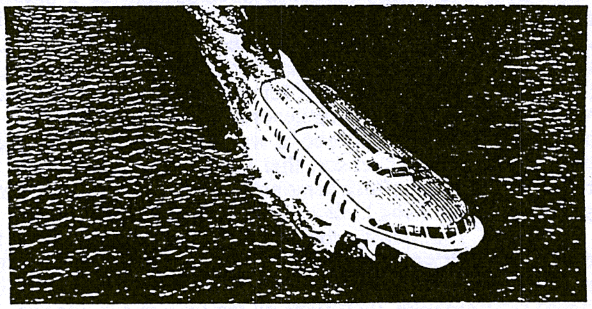


Figure 13 - SPUTNIK

Several military applications of hydrofoil ships were also introduced in this period. PCHELA was a 75 ton, 42 knot ship which carried anti-aircraft guns and a dipping sonar. The foil system consisted of surface-piercing bow foils with a horizontal center section between the main struts, which allowed operation in moderate sea states. TURYA and MATKA were both modifications to the successful OSA fast patrol boat hull design. Both of these ships where fitted with surface-piercing foils forward, but no foil aft. Thus, these ships were not true hydrofoils, since they were not designed for the hull to lift free of the water surface. The two ships differed in their mission, thus in their installed weapons systems. The ships displaced about 250 - 260 tons, and had a top speed of 40 to 45 knots.

1970 - 1992 The fast ferry TYPHOON was the first Soviet passenger vessel using gas turbines for propulsion power and a fully-submerged foil system with automatic controls to go into production. Placed in passenger service in 1972 for testing under commercial operating conditions, it went into production in 1975. This 65 ton craft carried 100 passengers at about 42 knots in calm water and 38 knots in 2 meter wave heights, demonstrating the speed advantage of hydrofoils in rough water.

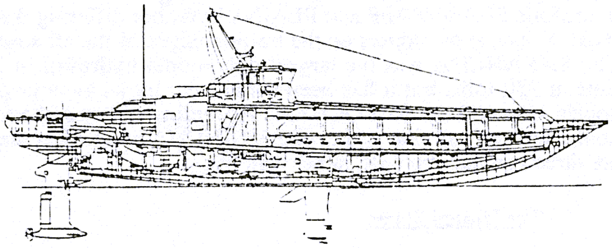


Figure 15 - Fast Ferry TYPHOON

In 1980 the KOLKHIDA, a replacement for the aging KOMETA class of high speed passenger ferries, was introduced. The foil system is an improvement on the augmented surface-piercing type system used on KOMETA. The improvements include the use of an automatic foil control system. KOLKHIDA is faster than KOMETA, seats more passengers, uses less fuel and can operate foilborne in rougher water.

The CYCLONE, an enlarged, double deck adaptation of the KOMETA class, will seat 250 passengers. This 140 ton ship is driven by two 5000 HP gas turbines. The foil system is the latest evolutionary version of the Alexeyev system described for the KOMETA. This version uses flaps, controlled by a sonic-electronic control system, to improve the ride quality .

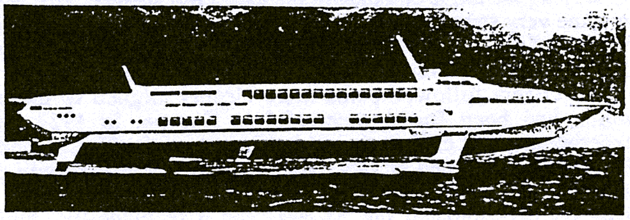


Figure 16 - CYCLONE

On the military side, the MATKA class was introduced in 1977. These ships are essentially the same as the TURYA except for the upgraded weapons suite. The SARANCHA class,

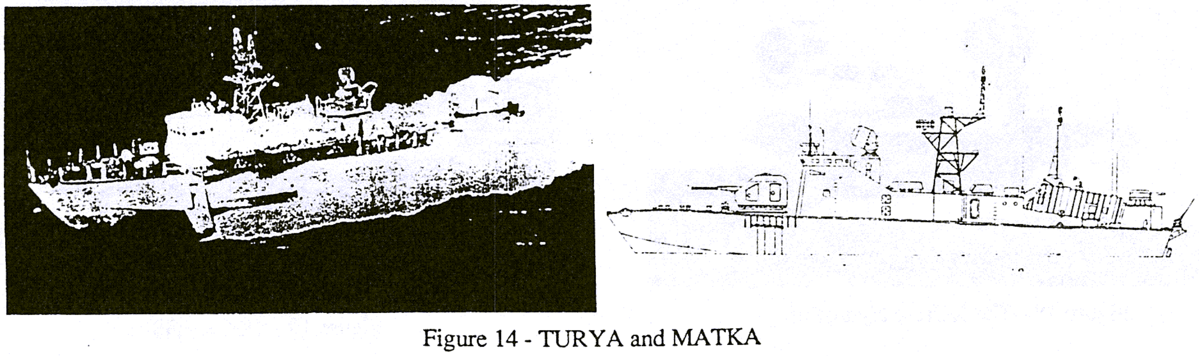


Figure 14 - TURYA and MATKA

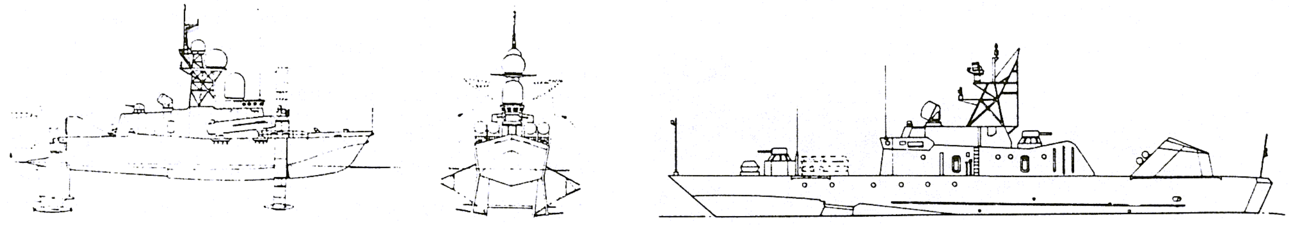


Figure 17 - SARANCHA and BABOCHKA

which also was introduced in 1977, is a 330 ton ship that uses a split V-type surface-piercing foil forward and a single fully submerged foil aft - very similar to the arrangement of the U.S. hydrofoils FLAGSTAFF and PLAINVIEW, but differing from those in its use of rudders on the trailing edges of the aft struts. The SARANCHA was the largest operational hydrofoil of its time at 330 tons, but it has been supplanted by an even larger cousin - the 400 ton BABOCHKA. According to Janes, the foil configuration is similar to that of SARANCHA except that there are three vertical struts aft, rather than two.

The United States

1950-1960 Hydrofoil research in the United States received little attention from the government until after WWII, when the work of von Schertel and Tietjens was recognized. The first efforts targeted the technology base necessary to support practical development work. Studies undertaken by various industrial, academic and government organizations covered foil section optimization, cavitation and ventilation effects, structural considerations, control aspects, etc. Numerous test craft of various sizes were developed during this period, to investigate and, hopefully demonstrate, the desirability of various foil configurations and control systems.

The success of these early efforts aroused great interest, and numerous hydrofoil initiatives followed. Control issues for ocean-going ships were given high priority. Many of the numerous test craft that were built and operated by various organizations in the years between 1954 and 1960 tested methods for achieving variable lift by incidence control; that is, by varying the angle of attack of the entire foil surface. This led to some very strange looking craft with long struts that reached forward of the hull to sense the incoming wave heights and vary the incidence of the foils to compensate appropriately.

Others followed paths more closely aligned to those which had been found successful in Europe. In 1954 an experimental test craft designed and built by John H. Carl and Sons attained a speed of 74.4 mph in smooth water, exceeding for the first time the record that had been set by Bell in 1916. This craft, designated the XCH-4, had a seaplane-like hull shape, and was powered by two aircraft engines and propellers which extended above the hull. The foils were individual V-shaped ladder foils on each side of the craft just forward of amidships, similar to a normal airplane configuration, and a single such foil aft.

Another interesting series of craft that were built and tested during this time frame were intended to provide high speeds for landing craft. Foils, which had to be retractable, were fitted to different amphibious vehicles. Variable depth, retractable propulsion systems were developed for some of these applications. Although solutions were found for most of the problems that were encountered, it ultimately became clear that the complexities and costs of the solutions represented too great a penalty to pay for the higher speed in the water.

An organization was formed to design and build a 3500-ton hydrofoil cargo carrier with a destroyer-type hull in the 1951 to 1954 time frame. After a major effort, involving capable experts from industry and government, the program was abandoned in 1954, largely due to the conclusion that the development of the propulsion system for such a craft would tax the total capability of U.S. industry.

Thus, by the mid-50s, while Europeans had progressed to the point where hydrofoils using surface-piercing foil systems were in commercial service, and were moving ahead to build and operate ever larger versions of their successful designs, in North America, research efforts and various smaller test craft to develop the data necessary to proceed to larger scale tests and full scale application efforts were just reaching fruition.

One of the most important developmental efforts in the U.S. during the 1950s involved development of a practical control system for fully-submerged foil systems. Since a fully-submerged foil system is not self-stabilizing in height or roll, as ladder-like or V-shaped surface-piercing configurations are, an independent system is needed for measuring the height above water and controlling the lift generated by the foils to keep the ship at a specified height above water and flying straight and level. A sonic height sensor, that was designed as part of the program, was successfully demonstrated on a test craft designed by Gibbs and Cox and built at Bath Iron Works.

With the knowledge gained from this effort, the designers undertook the modification of a small Chris Craft motor vessel, to outfit it with fully submerged foils arranged in a Canard configuration, with flaps on the foils to provide variable lift forces, with a sonic height sensor, and with an electronic autopilot stabilization system developed by the Draper Laboratory of MIT. This craft, named SEA LEGS, made its first flight in 1957. It demonstrated excellent seakeeping performance in rough seas at speeds up to 27 knots. SEA LEGS became the

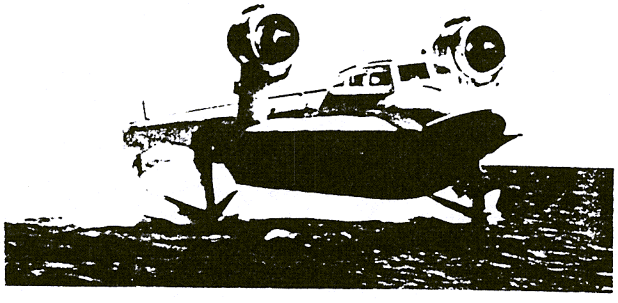


Figure 18 - The XCH-4 Hydrofoil

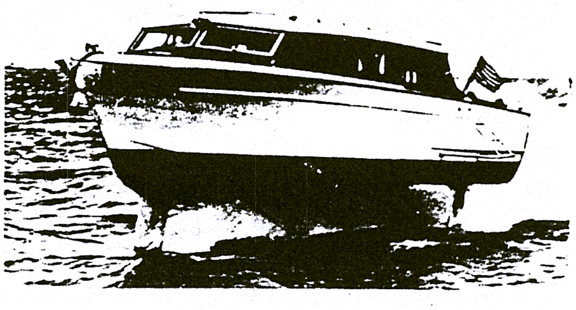


Figure 19 - SEA LEGS

demonstrator of hydrofoil feasibility and capability to the senior levels of the U.S. Navy, clearly demonstrating superior speed and seakeeping compared to its larger escort during an ocean-going trip from New York to Washington, DC.

The success of SEA LEGS undoubtedly played a major part in generating serious interest in the U.S. Navy for hydrofoils. One of the authors became a believer in hydrofoils with submerged foil systems after one ride through the combined wakes of three New York harbor tugs on SEA LEGS, when there was virtually no evidence of any motion aboard this little 20 foot boat!

At the same time, interest in hydrofoils for commercial applications in the U.S. continued. In 1955, the Maritime Administration (MARAD) sponsored an extensive parametric study to determine the type of hydrofoil craft best suited to future express-cargo and passenger applications and to establish design criteria for such craft. Following design studies, the HS DENISON was built and launched in 1962. DENISON combined two surface piercing foils forward with a single fully-submerged foil aft. The ship was powered by a 14,000 HP gas turbine. Power was transmitted through a right-angle bevel-gear drive to a super-cavitating propeller. The spiral bevel gears represented the forefront of gear technology in the U.S. at the time. Due at least partially to a decrease in promised U.S. Navy funding, this program was discontinued after extensive, valuable operating data and experience were obtained.

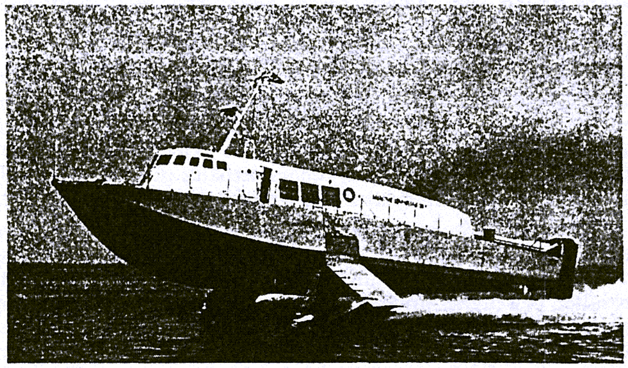


Figure 20 - HS DENISON

1960-1970 As a result of the successes of the DENISON and especially of SEA LEGS, the U.S. Navy identified approximately 10 million dollars for hydrofoil research and development in the early 1960s. Several different test craft and experimental prototypes of hydrofoil ships resulted from the ensuing efforts. These include the PCH-1, named HIGH POINT, which was designed for an antisubmarine warfare role and was equipped with a dunking sonar. HIGH POINT used fully submerged foils arranged in a canard configuration. Propulsion pods were located at the bottom of each of the two after struts. Each was configured with a propeller at each end.

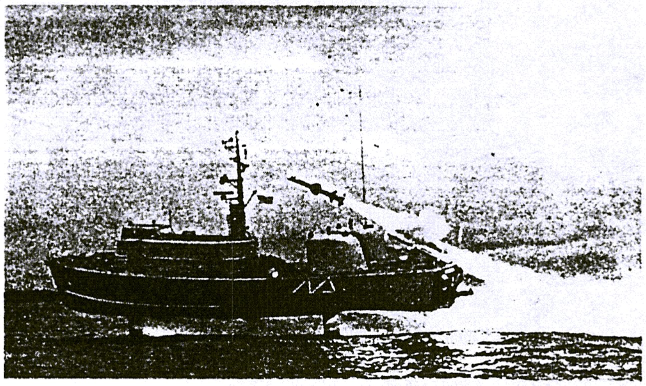


Figure 21 - HIGH POINT

This ship became the U.S. Navy's workhorse as a test platform for many different types of equipment intended for hydrofoil operation, from propeller blades to weapon systems. The first missile to be fired from a U.S. hydrofoil was from HIGH POINT. She was used to test variable depth towed sonars, towed array systems, torpedo firing from a high speed platform, and other systems. Numerous items of navigational equipment for high speed craft were tested first on HIGH POINT. The many accomplishments of this workhorse have been well documented by Ellsworth.

The high speed end of the performance envelope of hydrofoils was the target for other craft designed and built during this same early 1960s effort in the U.S. A test craft called FRESH-1 was built and used to test different foil configurations for very high speed operation.

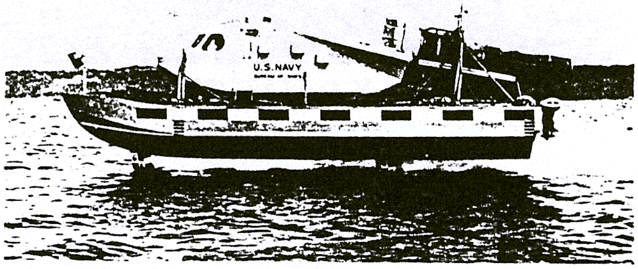


Figure 22 - FRESH-1

At about the same time, the U.S. Navy contracted for the design of a hydrofoil research ship designated the AGEH-1, which was ultimately named PLAINVIEW. This ship was configured to be capable of carrying four gas turbines, for achieving speeds up to 90 knots, with the hull designed for surviving crash landings at that speed. She was originally provided with two engines, and operated at speeds in the order of 50 knots, testing out supercavitating propellers, etc. PLAINVIEW, at 320 tons, with a length of 212 feet and a beam of almost 71 feet, was the largest hydrofoil ship in the world at that time.

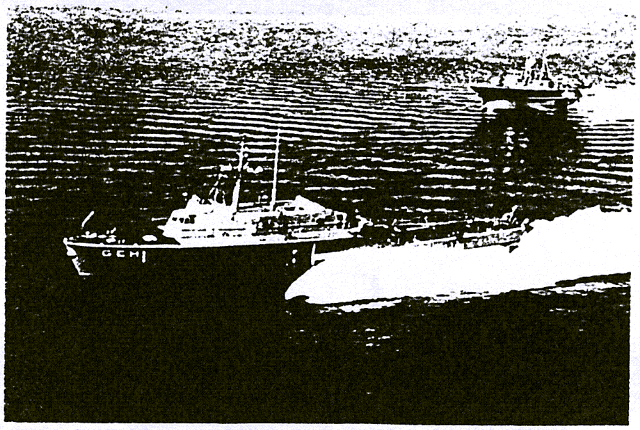


Figure 23 - PLAINVIEW

Although very much smaller in size, two hydrofoil patrol gunboats designed, built and operated in this same time-frame, made a very large impact on the future direction of hydrofoil development in the U.S. and in other countries, as well. The configurations of these two craft were very different, despite being designed and built to the exact same specifications. The FLAGSTAFF, PGH-1, designed and built by the Grumman Corporation, was propeller driven and used a conventional, airplane configuration for the foils. The PGH-2, TUCUMCARI, a Boeing product, was waterjet propelled and used a canard configuration. Both used fully- submerged foils, displaced 60 to

70 tons and had a length just under 75 feet. Both of these ships operated very satisfactorily. They both saw service in Vietnam between September 1969 and February 1970, making them the first U.S. Navy hydrofoils in combat.

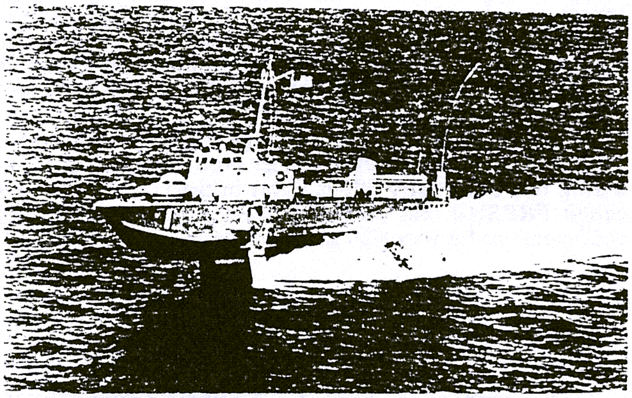


Figure 24 - FLAGSTAFF (PGH-1)

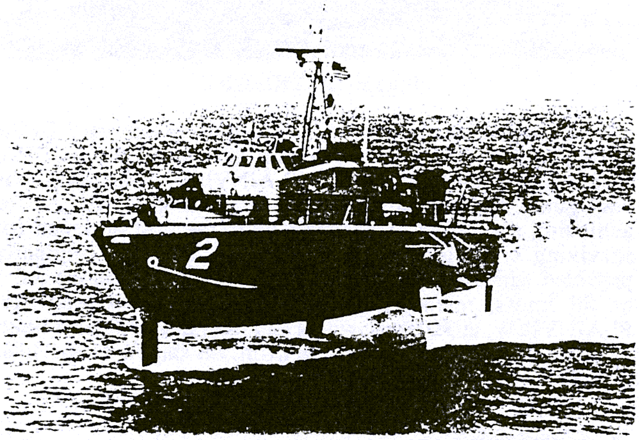
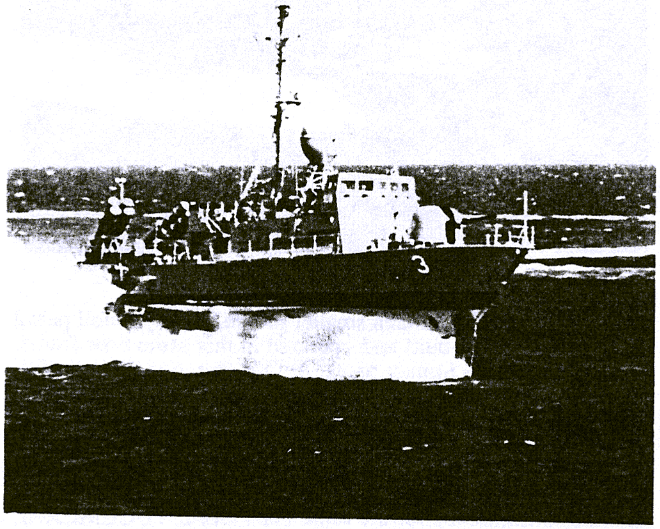


Figure 25 - TUCUMCARI (PGH-2)

1970 - 1992 The culmination of all of the research carried out in the U.S. during the 1960s was the NATO PHM program. This program was the outcome of a NATO project to produce a high speed missile carrying patrol craft suitable for operation in restricted waters, such as the Mediterranean, North Sea and Baltic waters. After about a year of deliberation in NATO on the mission of the required ship, a decision was made to select the patrol craft mission rather than an anti-submarine mission. The decision rested partly on the fact that the anti-submarine mission would have required larger, more expensive ships. The final mission decision, and the final selection of the ultimate team members of the program, was made after the members had agreed that, in order to vote, a country would have to agree in advance to share equally in the development costs of the ship for the mission they supported. Of the eight nations who participated in the early stages of the NATO project, only Germany, Italy and the U.S. participated in the actual design effort for the PHM. Italy and Germany also each provided three capable persons to the staff of the PHM Program Manager in Washington, DC. Each of these three nations provisionally committed to participation in a production program, which was to include the use of equipment from each of the participating countries.

Although Italy found it necessary to drop out of the production program before completion of construction of the first ships, the guns used on the lead ship of the PHM class were Italian Oto Melara 76mm guns. The ship's hullborne engines are German MTU diesels. The fire control system chosen was also a European product, from Holland's Signal Apparaaten, which was similar to equipment already in use in the German and Italian navies. The ship was designed in the metric system - the first, and unfortunately, still the only, metric ship built for the U.S. Navy in the U.S. to date. The design of the PHM followed closely the characteristics of TUCUMCARI, in that the canard foil system and waterjet propulsion were used.

The U.S. initially failed to follow through on its preliminary commitment to a production program for PHMs. This reduction in the number of ships that would be built resulted in a higher price per ship than the original program had planned. This, not surprisingly, was at least part of the reason for a decision made by the Federal Republic of Germany to cancel plans for further participation in the program. The U.S. later reversed its decision and ultimately ordered five more PHMs to be built. These ships are operational in Key West, Florida and have been particularly effective in combating drug smuggling boats in the Caribbean.



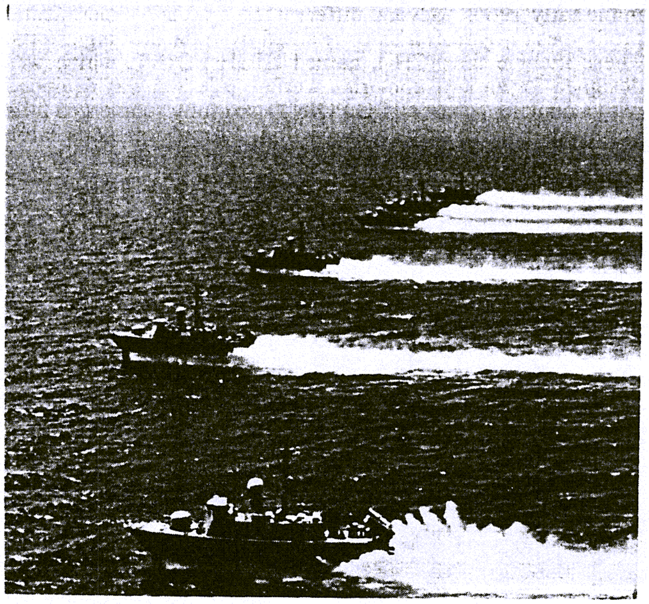


Figure 26 - USS TAURUS (PHM-3) and Six PHMs in Formation Flight

Following closely behind their efforts on the PHM Program, the Boeing Company, which had also participated in much of the Navy's testing efforts of the 1950s and 1960s, as well as accomplishing significant research of their own, designed and built commercial passenger carrying hydrofoils in the 1970s. The design of these craft, while different in many specific respects from the PHMs, also derive many similarities from the TUCUMCARI configuration. After building and selling about 30 JETFOILS, the Boeing Company disestablished its marine division and sold the rights to the JETFOIL to Kawasaki Heavy Industries about 1987.

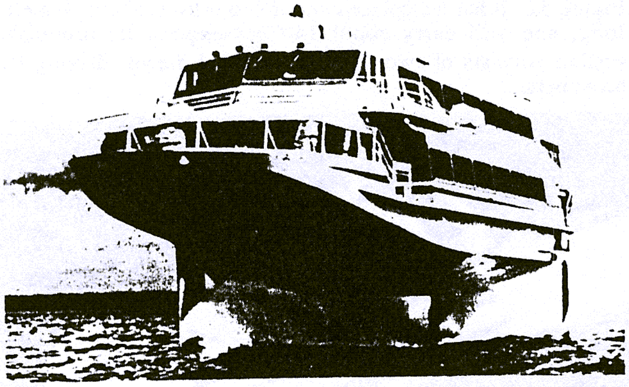


Figure 27 - JETFOIL

Canada

1950-1960 In the post W.WII period, Canadians also rekindled their interest in hydrofoils. In 1951, after some prior research and design efforts, a project was initiated at the Naval Research Establishment (NRE) to demonstrate the military potential of hydrofoils. A couple of test craft were built and fitted with various foil configurations. A right angle bevel gear drive, housed in the strut of the after foil, was successfully developed for the propulsion system of one of the test craft. These tests led the Canadians to conclude that the airplane configuration is not the best approach to use for surface piercing hydrofoils operating in rough seas. They concluded that the Canard configuration, with the main lifting surface aft and a smaller foil forward, was essential for good seakeeping with surface-piercing foils. This conclusion oriented the future developmental efforts on hydrofoils in Canada.

The Canadian requirement for a hydrofoil centered about the Anti-Submarine Warfare role, which demands an extremely versatile ship. Eames points out that an alternative to improving sonar range (on large ships) is to provide a significantly larger number of sonars economically. The stability of the hydrofoil, hullborne and foilborne, makes it the smallest ship capable of sustained operations in the open ocean. With this philosophy, and with the results of the tests described above, in 1959 the Navy authorized a study to develop the design requirements for a 200 ton ASW hydrofoil ship.

1960-1970 Canada invited experts from the United Kingdom and the United States to review the results of the ASW hydrofoil ship design study. All agreed that the concepts were sound. Those involved were aware that the US was proceeding with their 120 ton ASW hydrofoil ship, PCH-1, and that the two concepts were very different in almost every aspect, but it was agreed that both approaches were complementary, that it was impossible at that time to predict which would be most successful and that much more data would be obtained by pursuing both projects. Thus, in August 1960 a feasibility study for this ship was authorized. Separate contracts for a Preliminary Design, a Contract Design and, ultimately for Detail Design and Construction followed. The Canadians continued to invite U.S. and UK experts to their design reviews and to welcome comments. The foil system consisted of a relatively small diamond-shaped surface-piercing foil in the very bow and a large combined surface-piercing and submerged foil combination aft. The after foil provided 90 percent of lift, and the forward foil was steerable. In 1964, a fire in the main machinery space almost caused termination of the program, but the FHE-400, BRAS D'OR, was completed in 1967.

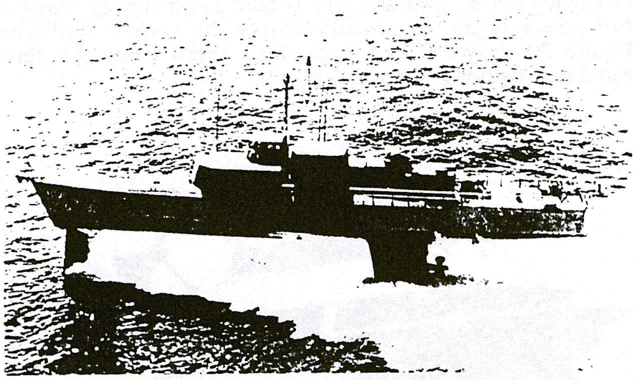


Figure 28 - Canadian BRAS D'OR, FHE-400

The trial program, conducted from 1968 through 1971, proved quite successful. A policy shift in the Canadian government downgrading the priority of ASW led to the curtailment of the FHE-400 program. BRAS D'OR still represents the most sophisticated and advanced design of a surface-piercing type hydrofoil.

Israel

The Israeli Navy had also watched the development of the U.S. Navy's two PGHs and in 1977 contracted with the Grumman Aerospace Corporation to design and build the first of a series of hydrofoils based on the FLAGSTAFF. The first ship of this class, the SHIMRIT, was built by Grumman in Florida and delivered in 1981. The follow-on ships of this class were built in Israel, the first one having been launched in the latter half of 1982. The foil configuration of these ships is essentially the same as that of FLAGSTAFF, but the control system, propulsion system and weapons systems all are modern, high technology upgrades.

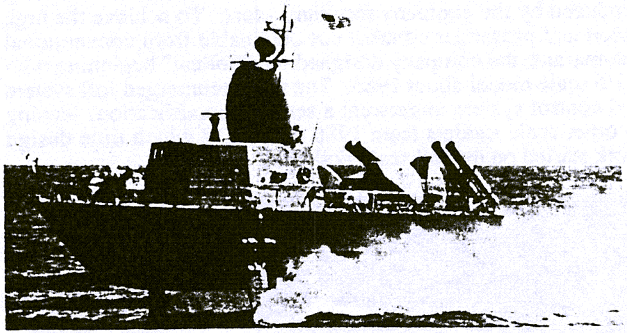


Figure 29 - SHIMRIT

Japan

Japan's interest in hydrofoils has been limited to research into hydrodynamic basics until the last few years. However, hydrofoils built in Europe have been used in various routes in Asia for some time. In 1987, Kawasaki entered into an agreement with the Boeing Company for the rights to build JETFOILs in Japan. These craft are operating successfully on several routes within the islands of Japan. We are fortunate to be able to have a report on this program and their Techno-Superliner Hybrid program as a part of this Conference.

RECENT DEVELOPMENTS

Westfoil 25

The salient feature of the Westfoil 25 hydrofoil is the patented drive system which uses both water and air propellers. Westfoil International, the only organization in the U.S. developing a hydrofoil, claims that this innovation improves efficiency during take off. The system automatically transfers full power to the air propellers once the craft is foilborne. Figure 30 shows a 24.4 meter high speed passenger ferry capable of carrying 149 to 180 people.

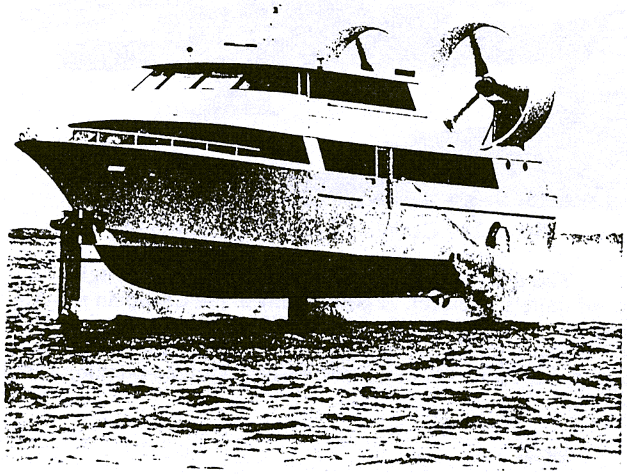


Figure 30- Westfoil 25 Hydrofoil

Four Detroit Diesel 12V-92TA diesels each deliver about 1,000 hp during take off and about 850 hp when the craft is foilborne. The engines drive a pair of shrouded air propellers; Arneson drives and a bow thruster are used for hullborne maneuvering. Trials of the craft were started in mid-1991 after a 4 1/2 year development program.

Foil Catamarans

Kvaerner Fjellstrand of Norway, has been developing a hydrofoil using a catamaran hull which has been the hullform produced by the company for many years. To achieve the high speed and passenger comfort not obtainable from conventional catamarans, the company designed the "Foilcat" beginning with a 1:5 scale model about 1985. The fully-submerged foil system and control system underwent a series of modifications leading to other scale models from 1986 to 1989 at which time design work started on the full scale Foilcat.

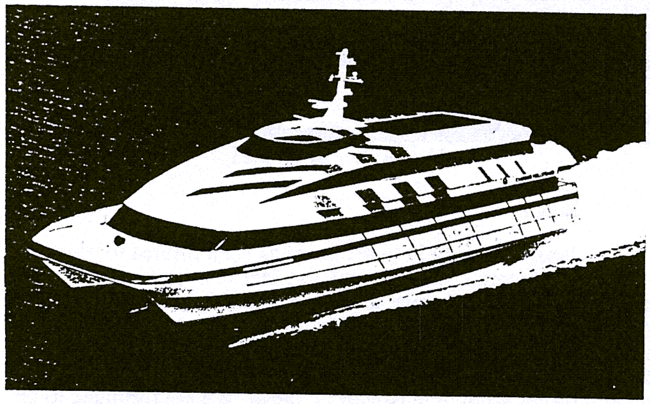


Figure 31 - Kvaerner Fjellstrand Foilcat

The 40 meter, 470 ton craft, shown in Figure 31, will carry between 300 and 449 passengers on two decks. The two short struts forward connect low aspect ratio foils to the catamaran hulls. A single, high aspect ratio aft foil spans the width of the vehicle and is connected to the hull with three aft struts. All foils are equipped with 20% chord flaps. Propulsion is provided by two LM500 gas turbines rated at 6,000 horsepower each, driving two KaMeWa S 80 II waterjets via Maag gear boxes. This high speed passenger ferry is expected to attain 50 knots in calm water and have excellent motion characteristics in waves.

Westamarin of Norway, is also developing a high speed foil catamaran passenger ferry, referred to as "Foilcat 2900", see Figure 32. It has a displacement of 115 tons, is about 30 meters long, and will carry about 140 passengers. Its propulsion system consists of two 2,000 KW MTU diesels driving two propellers.

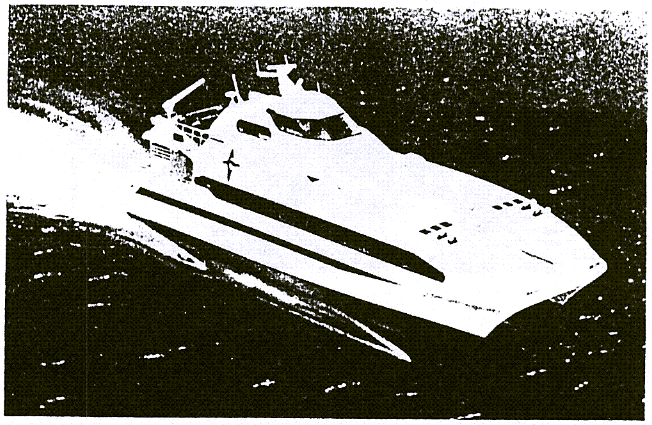


Figure 32 - Westamarin "Foilcat 2900"

A third foil catamaran, "Super Shuttle 400", shown in Figure 33, is under design by Mitsubishi Heavy Industries. This 40 knot high speed passenger ferry will displace 350 tonnes, have a length of 34 meters, and accommodate 350 passengers. Propulsion will be provided by four Mitsubishi diesel engines driving waterjets.

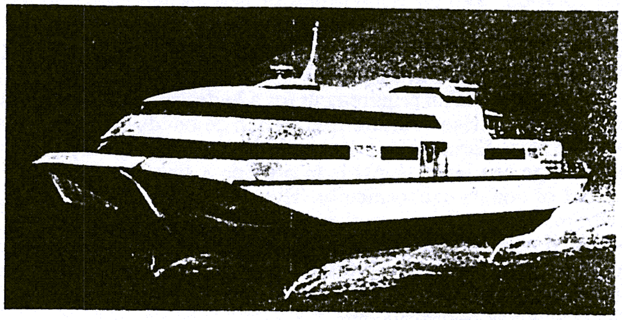


Figure 33 - Mitsubishi Super Shuttle 400

Rodriquez MEC 1 Hydrofoil

The MEC (Maximum Efficiency Craft) is the first of a range of hydrofoils planned by Rodriquez featuring hydrostatic propulsion. The power flow from the Hydromarine hydrostatic transmission system is via hydraulic pumps and hoses. This "hydraulic drive" therefore eliminates the usual angled shaft or Z-drive. The 25 meter long MEC 1, shown in Figure 34, has two 845 KW diesels each one of which drives a tractor propeller. The surface-piercing foils of the MEC 1 are scheduled to be replaced by a fully-submerged foil system later in 1992.

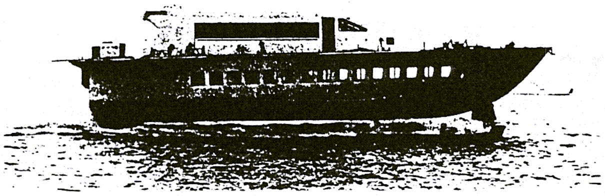


Figure 34 - Rodriquez MEC 1 Hydrofoil

Hydrofoils Worldwide

Several years ago it was anticipated that there would be many more hydrofoils in use, both military and commercial. Although the numbers may not have come up to expectations, in retrospect, the "Grand Total" worldwide is not small. The sources for the numbers in Table I include recent issues of Fast Ferry International and Jane's High Speed Marine Craft. It should be noted that the numbers of hydrofoils in the vast area previously known as the Soviet Union are uncertain, and probably larger than the values reported.

PHM Growth

The PHM ships currently in the squadron are scheduled to continue operations as presently configured until the year 2003. Improvements can be made in these ships to increase their range, improve their motion control system, and introduce a variety of payloads to broaden their mission applications. Studies were made in the late 1980s to examine the potential of a PHM "Growth" hydrofoil shown in Figure 35.

The ship is 400 tons instead of 240 tons, and is "stretched" from 138 feet to 160 feet. As in the aircraft world, Boeing has suggested putting a 22 foot long plug in the hull. The ship would use the full available power of the LM 2500 gas turbine engine, namely 25,000 hp, to maintain the PHMs speed, and carry more fuel. All of this would result in a larger payload, or combat system, and greater range and endurance. Other studies have been made which describe a wide variety of PHM variants and the roles these ships could play in the real world.

Table I - Worldwide Summary of Hydrofoils

Military	Built	In Service
U.S. Navy	6	6
Commonwealth of Independent States (Soviets)		
Pchela	2	2
Turya	30	30
Matka	16	16
Sarancha (NATO code name)	1	1
Babochka	1	1
Muravey	1 +	1 +
Italian (Sparrero Class)	7	7
Israeli	2	2
TOTAL MILITARY	66	66
Commercial		
Boeing		
Jetfoil 929-100 (built 1974-77)	10	10
Jetfoil 929-115 (built 1977-86)	18	12
Hitachi		
PT 20 (built 1962-81)	17	4
PT 50 (built 1964-83)	25	17
Kawasaki		
Jetfoil 929-117 (built 1989-)	11	11
Rodriquez		
PT 20 (built 1965-71)	48	22
PT 50 (built 1959-70)	29	16
RHS 70 (built 1972-82)	10	10
RHS 110 (built 1970-75)	5	1
RHS 140 (built 1971-77)	13	6
RHS 150F (built 1983-)	3	3
RHS 150 FL (built 1988-)	3	3
RHS 150 SL (built 1979-84)	6	6
RHS 160 (built 1975-82)	9	8
RHS 160 F (built 1984-90)	18	15
RHS 200 (built 1981-)	2	2
MEC 2-200	1	1
Rodriquez/Hyundai		
RHS 70 (built 1985)	1	1
Seaflight H.57 (built 1968-69)	6	2
Westermoen PT 50 (built 1962-68)	3	1
Kolkhida (built 1983-)	30	19*
Kometa (built 1964-83)	130	100*
Meteor	7	7*
Raketa (built 1957-)	500*	?
Voskhod (built 1969-)	9*	9*
Cyclone (built 1985-)	?	?
TOTAL COMMERCIAL	914*	287*
GRAND TOTAL	980	353

POSSIBLE FUTURE HYDROFOIL DESIGNS

It is regrettable to say that since development, production, and deployment of the PHM, JETFOIL, and SHIMRIT hydrofoils, advancement of hydrofoil technology in the United States, and particularly the U.S. Navy, from the mid-1980s has been restricted to essentially "paper studies". The desire on the part of hydrofoil technologists for more research and development to reduce cost and improve performance has not been shared by those decision makers having control of research and development funding. Priorities have been placed elsewhere, but the hydrofoil community has had an opportunity from time to time to provide conceptual studies, feasibility designs of hydrofoils to suit a variety of purposes and missions. Within the constraints of national security, this section will describe some of these endeavors. The reader should be aware that the list of "paper" hydrofoils described below is in no way complete, but those shown do represent the breadth of work that has been accomplished in this area.

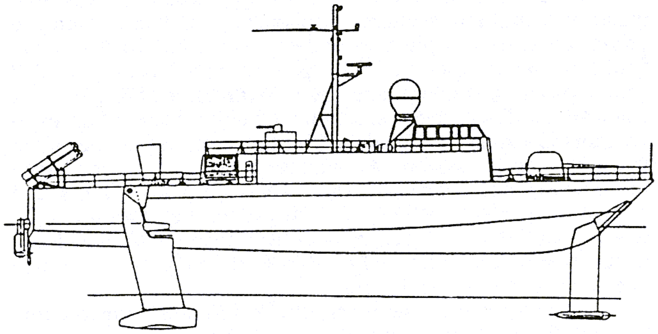


Figure 35- PHM Growth

Corvette Escort

The Corvette Escort hydrofoil design shown in Figure 36 was examined in the early 1980s. It is about 615 tons, is 196 feet long, has a maximum beam at the deck of about 39 feet, and a beam across the foils of 47.5 ft.. A unique feature of the ship is its propulsion and ship service power arrangement which makes it possible to meet the stringent requirements that were established. A normal-conducting electric transmission system is used instead of a gear and shaft arrangement. A single LM 2500 gas turbine engine drives two different sized electric generators. One of them, the larger, is connected electrically to two electric motors in the two propulsion pods at the bottom of the aft struts. The other generator provides electric service power for the entire ship.

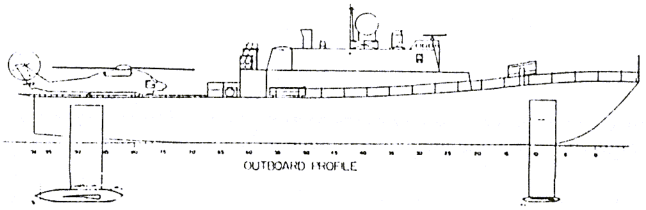


Figure 36 - Corvette Escort Hydrofoil

This U.S. Navy Corvette Escort hydrofoil design features a retractable, fully submerged Pi-type foil/strut system both forward and aft. Incorporation of an electric drive system mentioned above provides arrangement flexibility, thereby enabling a relatively large unobstructed aft deck for accommodation of a LAMPS III helicopter.

Mission equipment planned for the Corvette Escort hydrofoil includes: LAMPS III helicopter with reloading and refueling capability, high speed Depressor Towed Array System (DTAS) for detection, classification and tracking of targets, Expendable Reliable Acoustic Path Sonobuoy (ERAPS) for detection, classification and localization of submarines, sonobuoys, free-floating line arrays, Advanced Light Weight Torpedoes (ALWT), missiles, and electronic warfare equipment.

Although several propulsion system alternatives were explored during the early design work, the final selection consisted of a combined gas turbine or gas turbine (COGOG) using an LM2500 or TF40 combined propulsion and ship service system. The LM2500 drives a 16 megawatt (MW) normal conducting liquid-cooled generator and a 0.4 MW alternator. The 16 MW generator, in turn, is connected to two 8 MW liquid-cooled normal conducting motors located in pods at the aft foil/strut intersections. A planetary gearbox in each pod drives controllable pitch propellers for either hullborne or foilborne operation. A TF40 gas turbine drives a 4 MW generator and a 0.4 MW alternator. With the 4 MW generator connected to the propulsion motors, a hullborne speed of about 15 knots is estimated. The 0.4 MW alternators are connected to the ship's service system. An auxiliary power unit is provided for docking and maneuvering at speeds up to 8 knots and consists of a 510 hp P&W ST6J-70 gas turbine with outdrive. It was found that this total system maximized usable fuel and hence resulted in relatively large fuel margins and range compared to alternative designs.

The foil/strut system was of HY-130 steel construction. Several forward strut steering approaches were considered consisting of rotating struts, strut trailing edge flaps, circulation control, and ventilation control. This area has been identified as one in which R&D is required to resolve the steering problem on forward "Pi"-type foil systems.

Developmental Big Hydrofoil

During the 1970s, several U.S. Navy designs for hydrofoils of about 750 tons were studied for a trans-oceanic mission. These were referred to as the DBH, Developmental Big Hydrofoil; also dubbed the "Damn Big Hydrofoil". The study concluded that such hydrofoils could be constructed to meet specified performance criteria. Mission roles for which the DBH (shown in Figure 37) was designed include Anti-Submarine Warfare (ASW), Surface Warfare (SUW), and limited Anti-Air Warfare (AAW) for self defense as primary; shore bombardment, coastal patrol and surveillance and electronic warfare were secondary roles.

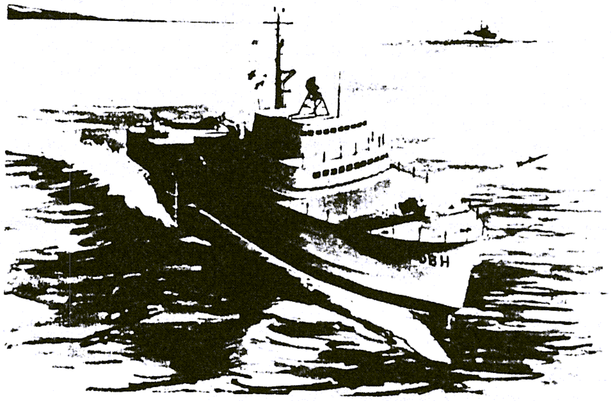


Figure 37 - DBH

Two LM2500 gas turbines power the ship in the foilborne mode. They drive through a right-angle transmission which permits both single and dual engine operation of both supercavitating pusher propellers. A unique feature of this design is an arrangement which allows the struts to retract about the input shaft axis without a disconnect coupling and permits propellers rotating in opposite directions. Hullborne propulsion is provided by two smaller gas turbine engines rated at 2,500 horsepower. Each one drives a controllable reversible pitch (CPR) propeller through reduction gears and a retractable outdrive.

The hull of the DBH is of a conventional planing form with a canard configured strut/foil system. The ship has an overall length of 173 ft and a maximum beam of 45 ft. With the foils retracted, the navigational draft is about 10 ft, whereas with the foils down, the hullborne draft of DBH is 39 ft. This contrasts with only 12 ft of draft when the ship is foilborne. Dynamic lift of 717 tons is provided by the foil system; the load is distributed 33% on the forward foil, 67% on the aft foil which has a span of 85.5 feet. The forward foil/strut system is an inverted "T" which retracts forward into the bow and the aft system is an inverted "Pi", retracting over the stern in the same manner as PHM. As in all hydrofoils with a fully-submerged foil system, an automatic control system is incorporated in DBH similar to that on the PHM.

A combat subsystem was selected to provide a "representative" assortment of weapons, surveillance and combat and control equipments for escort type vessels. The combat subsystem consists of: a MK 16 launcher (mounted aft), ASROC, HARPOON missiles, chaff dispensers, torpedo tubes, torpedoes, OTO MALARA 76mm cannon (mounted forward), 20mm Close-In Weapon System, and associated fire control systems.

Grumman HYD-2

In the late 1970s a major U.S. Navy study was undertaken to investigate a wide variety of advanced naval vehicles. Of the several hydrofoils studied, one was a design by the Grumman Aerospace Corporation: the HYD-2 shown in Figure 38. It was 2400 tons, 365 ft long, had a 116 ft aft foil span, and the aft deck was equipped with a helicopter hangar and landing pad. Its foilborne propulsion system used two Pratt and Whitney FT-9 gas turbines with a power output of 43,000 hp each.

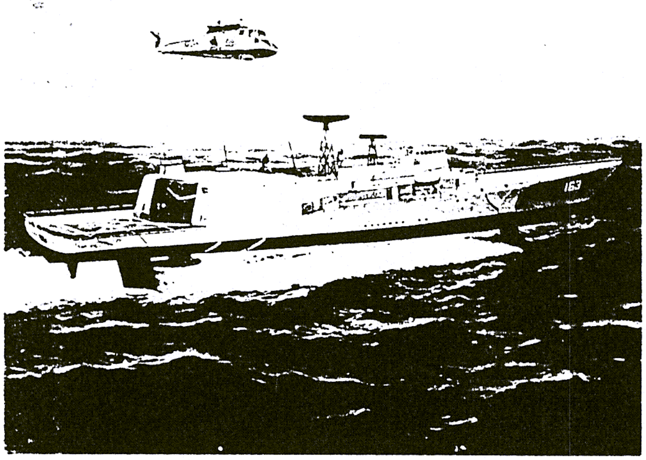


Figure 38- HYD-2 Hydrofoil

This 2,400 ton hydrofoil ship is predicted to be capable of achieving a maximum foilborne speed of 53.1 knots in calm water. In sea state 6, the speed is projected to be reduced only a small amount to 51.6 knots. The maximum foilborne range in calm water is 2,950 nm at 45 knots. The foilborne propulsion system drives two controllable pitch propellers through a combined transmission arrangement. Hullborne propulsion is provided by one General Electric LM500 gas turbine driving two identical propellers through the combined transmission arrangement. Maximum hullborne calm water speed is about 26 knots using one FT-9 or 15 knots with the LM500. The hullborne engine is rated at 4,650 horsepower continuous. Electric plant prime movers are three Lycoming TF-35 gas turbines rated at 2,800 horsepower each.

The foil system selected for the HYD-2 consists of two inverted "Pi" assemblies. The aft foil system supports 60% of the craft weight; the forward system, 40%. The aft assembly consists of a foil, two struts, two pods, housing the flap control mechanism and the power transmission, and two propellers located at the aft end of the pods. The two struts are mounted on either side of the hull; the system retracts in the aft direction. The forward system is similar but with smaller pods. A third pod is located at the forward foil root chord housing the foil folding mechanisms, and steering trunnions are located above the keel line for the steerable struts. All struts have NACA 16 series sections and constant chord over their length.

This vessel was designed to accommodate a variety of combat systems for various missions. The primary Anti-Aircraft Warfare (AAW) suite includes: advanced radar and fire control systems, multimode missiles, advanced vertical launching system, and advanced self-defense missiles with launchers. For the Surface Warfare (SUW) suite, HARPOON missiles are added. For the Anti-Submarine Warfare (ASW) suite the following items are added: various towed sonar arrays, MK 48 improved torpedoes, Advanced Lightweight Torpedoes (ALWT), and LAMPS MK III helicopter and associated equipment.

PCM

Two U.S. Navy hydrofoil design studies performed in the latter part of the 1980s includes the PCM, a patrol missile-carrying combatant, and a NATO hydrofoil. The PCM hydrofoil design illustrated in Figure 39 was intended to supplement the PHMs currently in the U.S. Fleet. Several variants of PCM were explored each to have a greater range than the PHM and some were to carry a more capable combat system. The entire Navy study also considered conventional monohull ships and Surface Effect Ships (SES). The PCM hydrofoil is about a 500-ton ship, and was much smaller than either the monohull or the SES projected to satisfy the same requirements. Power for foilborne operation would be one LM2500 gas turbine engine (as on the PHM except that the full power level of the engine would be utilized) but driving two propellers through a series of reduction gear boxes instead of the current PHM's waterjet. A separate propulsion system consisting of two diesel engines with retractable propellers would be used for hullborne operations.

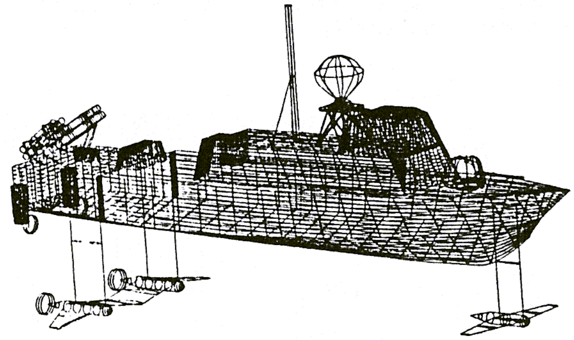


Figure 39- PCM Hydrofoil

Main foil span of the 147 ft PCM was to be about 61.5 ft with a hullborne draft of 28 ft with the foils extended and only about 8.3 ft with foils retracted. Instead of the 17-4PH stainless steel on PHM the PCM was designed to use a different material, namely HY-130 steel. Although this steel requires a coating, it was anticipated that some of the problems with PHM foil material could be avoided. It should be noted that in spite of the fact that PHM foils were not originally anticipated to require a coating, the Navy finally decided to paint the 17-4PH stainless steel to reduce foil maintenance costs.

The PCM crew was to consist of 4 officers, 1 Chief Petty Officer, and 24 enlisted personnel. This was only a small increase in the crew members carried by the PHM. This version of the PCM carried about the same combat system, but with technical improvements and weight savings. Several other variants of PCM were explored with more extensive combat systems.

NATO Hydrofoil

A hydrofoil study that was performed by the U.S. Navy for a NATO mission resulted in a ship in many respects similar to the PCM hydrofoil described above.

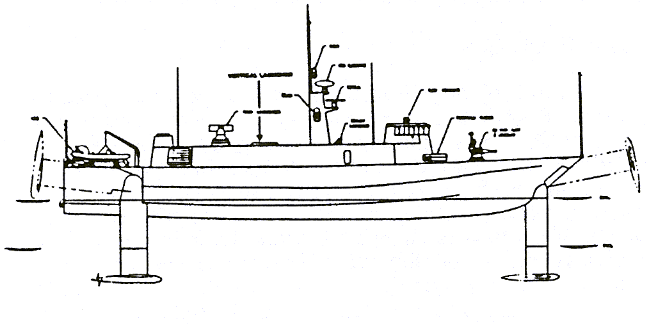


Figure 40 - NATO Hydrofoil

Shown in Figure 40, it is somewhat larger, however at 780 tons, is 196 feet long, has a greater range, more elaborate weapon system and a larger crew. Because of the NATO connection, two British Rolls Royce Spey gas turbine engines were selected at a rating of 15,000 hp each. The engines were interconnected to drive two propellers at the bottom of the aft struts through a series of gear boxes.

TECHNICAL ASPECTS OF HYDROFOILS

Hydrofoil Configurations

Surface-Piercing

Hydrofoil configurations can be divided into two general classifications: surface-piercing and fully-submerged, which describe how the lifting surfaces are arranged and operate. These are shown in Figure 41.

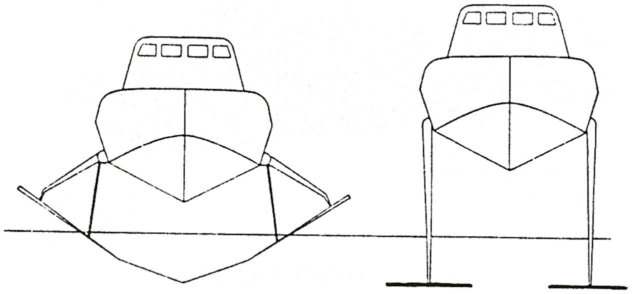


Figure 41- Hydrofoil Configurations

In the surface-piercing concept, portions of the foils are designed to extend through the air/sea interface when foilborne. Struts connect the foils to the hull of the ship with sufficient length to support the hull free of the water surface when operating at design speeds. As speed is increased, the lifting force generated by the water flow over the submerged portion of the foils increases causing the ship to rise and the submerged area of the foils to decrease. For a given speed the ship will rise until the lifting force equals the weight carried by the foils.

When the surface-piercing foil encounters a wave, varying amounts of the foil surfaces are submerged, and in order to maintain total lift equal to ship weight, the craft must either pitch, roll, or heave (or a combination of all three). These changes occur automatically, and therefore a surface-piercing foil system is said to be self-stabilizing. It therefore requires no active controls for height, longitudinal or roll stability. But it is this very attribute of the system that forces the hull to move and therefore places a limit on its ride quality if the ship is required to operate in very rough water. Modern surface-piercing hydrofoils have augmented their inherent stability with electrohydraulic automatic control systems to enable them to operate in higher sea states with a ride that is acceptable to the personnel aboard.

Fully-Submerged

The foils of the fully-submerged concept are designed to operate at all times under the water surface. The struts which connect the foils to hull and support it when the ship is foilborne generally do not contribute to the total hydrofoil system lifting force. In this configuration, the hydrofoil system is not self-stabilizing. Means must be provided to vary the effective angle of attack of the foils to change the lifting force in response to changing conditions of ship speed, weight and sea conditions. The principal and unique operational capability of hydrofoils with fully-submerged foils is the ability to uncouple the ship to a substantial degree from the effect of waves. This permits a relatively small hydrofoil ship to operate foilborne at high speed in open sea conditions normally encountered while maintaining a comfortable motion environment for the crew and passengers and permitting effective employment of military equipment. It is this desirable characteristic which has caused the hydrofoil ship development in the United States to concentrate on the fully-submerged foil concept.

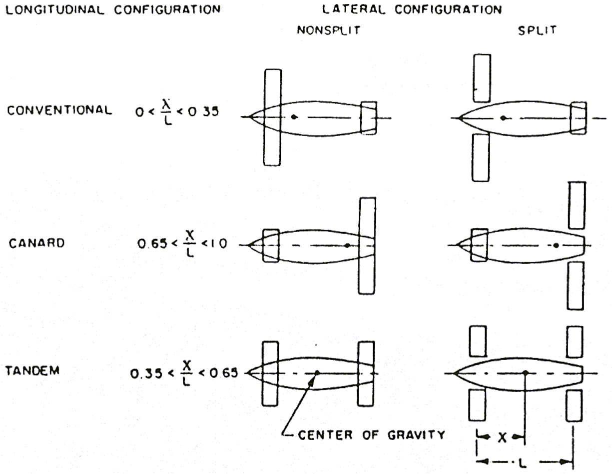


Figure 42 - Foil Arrangements

The basic choices in foil and strut arrangement are canard, conventional or tandem as shown in Figure 42. Generally ships are considered conventional or canard if 65% or more of the weight is supported on the forward or aft foil respectively. The conventional configuration is also referred to as an "airplane" arrangement. If the weight were distributed relatively evenly on the fore and aft foils, the configuration would be described as tandem.

Hydrofoil Characteristics

Resistance and Powering

Figure 43 shows typical resistance curves for a planing hull and hydrofoil craft. The implication of the term "bare" on the planing hull curve means that it does not include the drag of appendages such as propeller shaft, shaft supports, and rudders. On the other hand, the hydrofoil craft curve does include everything that is in the water. The "propeller thrust" line in Figure 43 is a typical trend line representing the reduction of propeller thrust as speed increases for a given power setting of

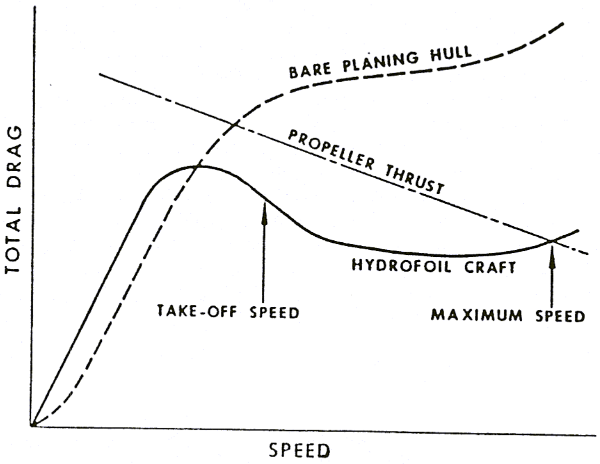


Figure 43 - Drag Comparisons

the engine. It can be seen that the planing hull craft will require relatively more power to raise the propeller thrust curve upward to achieve a crossing with the drag curve at the higher speed of the hydrofoil. It can also be seen that the hydrofoil generally has a higher drag at low speeds, but upon takeoff, drag rapidly decreases, reaches a minimum, and then rises again until propeller (or waterjet) thrust available equals drag, at which time the hydrofoil reaches its maximum speed.

The reason for the greater drag of a hydrofoil at low speeds is because of the submerged struts and foils which add to the drag of the hull. Just before takeoff, the foils are required to produce lift equal to the total weight of the craft. This is difficult to do at low speeds since large angles of attack are necessary on the foils and this produces high drag (induced drag, or drag due to lift). Since lift on the foil varies with the square of speed, foil angle of attack can be reduced quite rapidly after takeoff, induced drag decreases, and the hydrofoil speed increases. In addition, the hull is no longer in the water, and therefore its drag is eliminated which further contributes to reduction of drag after takeoff.

Although the major reason for the employment of hydrofoils is to lift the hull out of the water to reduce the effect of waves and to reduce the drag at high speed, a naval hydrofoil ship spends a considerable portion of its life hullborne and must have an efficient hull form to keep the drag low at low speed and through takeoff. Total drag just prior to takeoff is a significant factor in establishing the power requirement. Careful attention must be paid to the hull design to minimize this effect. To overcome additional takeoff drag which results from rough water, a power margin over the smooth-water takeoff drag 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 to permit takeoff in rough water in any direction.

As an example of drag build-up of a hydrofoil, data from PCH-1 (HIGH POINT) is shown in Figure 44. The lift system drag includes drag associated with the lifting surfaces (foils) and that of the associated appendages such as struts, pods and fairings, required to connect the foils to the hull. The drag of the lift system can be divided into two major components:

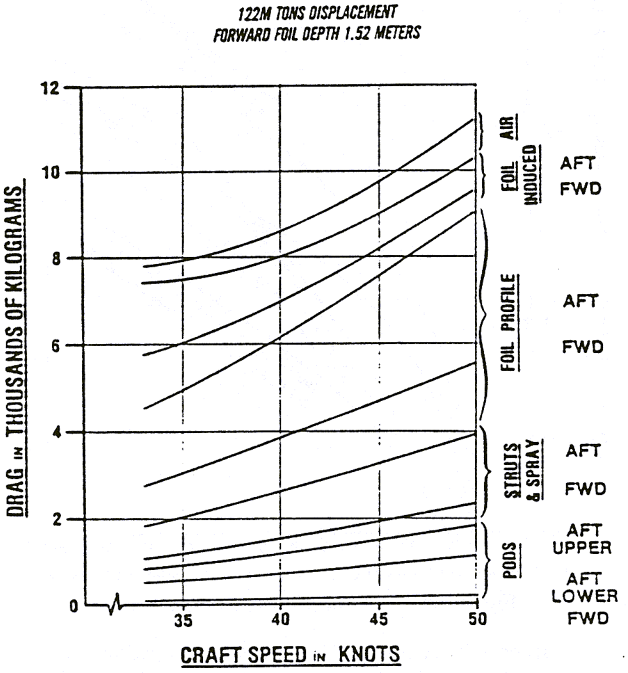


Figure 44 - PCH-1 Hydrofoil Drag Build-Up

1. Zero lift drag, or parasite drag, including the section profile drag, the effects of fluid friction and flow separation associated with the development of the boundary layer, spray drag, and air drag on the hull.

2. Drag due to lift which includes the induced drag (associated with the energy of the downwash in the wake of a lifting surface) and wave drag (associated with the energy in the wave produced on the free surface).

The zero lift drag varies with V^2, making this the predominant drag at high speed. The drag due to lift, on the other hand, varies as l/V^2, making it predominant at low speeds. In fact, when combined, there is a speed at which the drag is a minimum which, for most hydrofoils, occurs from 5 to 10 knots above takeoff speed, as shown in Figure 45 for a typical lift system designed to carry 1,000 tons on two equal foils at a maximum speed of 50 knots. The drag due to lift is also inversely proportional to the foil aspect ratio, defined as the foil span divided by its chord. Therefore, from a hydrodynamic efficiency viewpoint, the span of a hydrofoil should be as great as practical, particularly for drag reduction at takeoff and lower flying speeds. However, at higher flying speeds, where the required lift coefficient is much smaller, a shorter foil span (and foil area) is desired to minimize friction drag. The resulting foil geometry is therefore a compromise between the two operating speed regimes. Additionally, structural and other considerations limit the practical span of the foils. For example, foil span in some studies of very large hydrofoils has been limited to 100-104 ft. to allow the ships to pass through the Panama Canal. Also, it is recognized that a substantial foil overhang on either inverted "T" (single strut) or inverted "P" (two struts) foils could interfere with piers and other adjacent ships. These practical factors force the designer toward a tandem configuration on larger hydrofoils and to maintain span and overhang to acceptable values. PHM, for instance, utilizes a floating platform between it and the pier to accommodate its aft foil overhang.

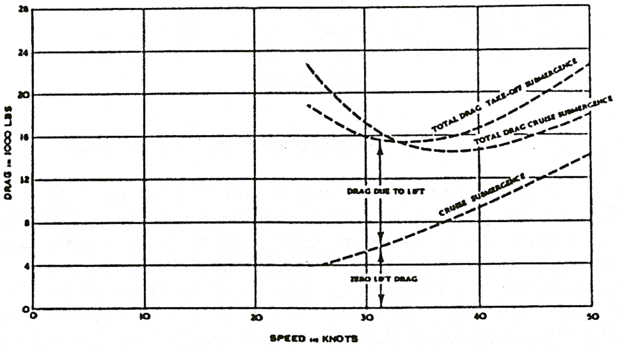


Figure 45 - Large Hydrofoil Drag Breakdown

Hydrofoil ships with their foils down have a greater draft than conventional hulls of the same displacement. For the 240-ton PHM this is 23 feet, whereas a 1,000-ton hydrofoil ship, the draft may be approximately 35 feet, about 2/3 of which is the amount the foil-strut system projects below the keel. If it is required that this draft be reduced and the lift system and propulsion gearboxes be accessible for maintenance without drydocking, it is then necessary to retract the foils out of the water. For larger hydrofoil ships, this is most easily done by rotating the foils up behind the transom and up over the bow. Design studies for very large hydrofoil ships indicate the weight penalty for dry retraction can be as much as 10 to 20% of the full-load weight of the ship. HIGH POINT PCH-1 had a wet retraction system, and therefore when maintenance of the gears in the propulsion pods was required, the hydrofoil was lifted onto a high cradle at pierside.

A foil design is very similar to a wing design except the hydrodynamicist has to cope with cavitation. whereas the aerodynamicist has to cope with compressibility. Although both are physically unrelated, the restrictions imposed upon foil design by cavitation are analogous to those imposed by Mach-Number effects on wing design. Thus, a cavitation bucket looks very similar to a Mach force-divergence bucket. Cavitation occurs when the local static pressure drops below vapor pressure, and vapor cavities are formed. These cavities increase drag and may collapse on the surface of the foil resulting in severe erosion. The prediction of hydrodynamic forces and moments are now normally obtained from computer programs which generate the pressure distribution on the foil based on lifting-surface theory to assist in optimizing design performance.

Foil loading (dynamic lift divided by foil planform area) is first established at takeoff speed and/or minimum specified flying speed. The maximum lift coefficient which can be achieved by a foil is generally around 1.0. About 20% to 30% of this is reserved for control forces needed at takeoff, to counter the seaway, maneuvering and takeoff trim requirements.

Figure 46 shows the relationship of foil loading to takeoff speed. The limits are based on lift coefficients of 0.7 and 0.8. The minimum stable flying speed shown generally corresponds to a speed a few knots below the speed of minimum drag. This corresponds to a lift coefficient between 0.5 and 0.6, which provides sufficient lift margin needed to assure necessary control forces to trim the ship, alleviate seaway disturbances and provide maneuvering transient forces and moments.

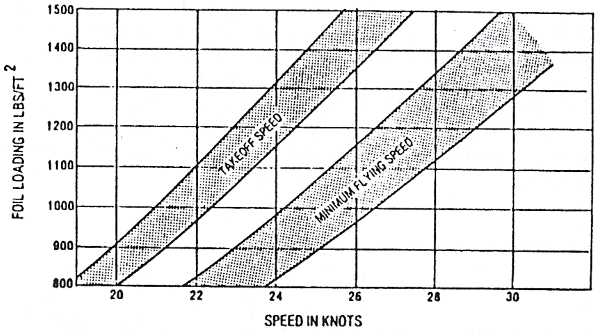


Figure 46 - Foil Loading and Minimum Flying Speed

A particular foil section is selected so as to give a relatively flat pressure-distribution curve across the foil chord. This avoids a local pressure peak with resultant cavitation. Although both the NACA 16 series and 64 series have this characteristic, the 16 series has been used for Navy hydrofoils primarily because of the extent of data available. Further, it is relatively thicker where the hinge line for the trailing-edge flap is located. Figure 47 is a plot of an operating foilborne loading-speed envelope with a cavitation boundary plot of a selected foil section superimposed. This shows that for a 0.35 camber, the foil will cavitate slightly at minimum speed and maximum weight, particularly in a seaway. If the camber is increased to 0.40, however, the entire steady-state envelope will fall within the cavitation-free area, and only slight intermittent cavitation will occur in a seaway. The same result could have been achieved by lowering the foil loading slightly. Decreasing the foil loading, however, increases foil size and weight. In selecting a foil section, the designer can favor either speed margin or weight margin. Since most ships tend to grow in weight with time, weight margin is considered the preferred option.

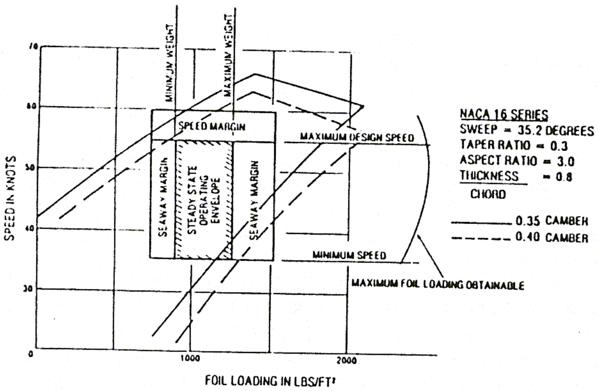


Figure 47 - Foil Loading-Speed Envelope

Seakeeping

Some of the principle advantages of hydrofoil ships, over monohull or other alternative ship types are: (1) the ability of a ship, which is small by conventional ship standards, to operate effectively in nearly all sea environments, and (2) an improved ratio of power to displacement in the 30 to 50 knot speed range permitting economical operation at these higher speeds. The submerged-foil ship can maintain its speed and maneuverability in heavy seas while simultaneously providing a comfortable working environment for the crew. The ship's automatic control system (ACS) provides continuous dynamic control of the ship during takeoff, landing, and all foilborne operations. In addition to providing ship roll and pitch stability, the ACS controls the hull height above the water surface, provides the proper amount of banking in turns and all but eliminates ship motions caused by the orbital particle motion of waves. Foilborne operations only become limited as wave height exceeds the hydrofoil's strut length.

Motions data show that hydrofoils with fully-submerged foils provide a superior ride at high speed with vertical, pitch and roll motions much less than larger conventional ships. This, for example, is given in Figure 48.

Long-Term Vertical Acceleration Distributions in the North Sea

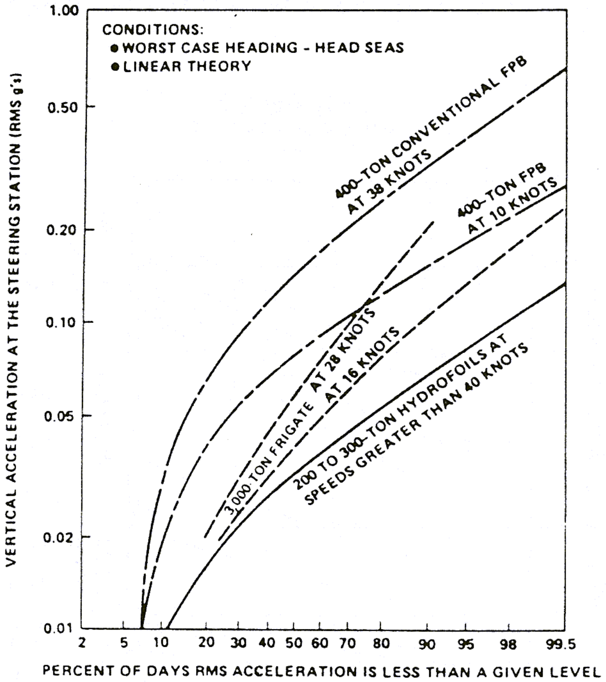


Figure 48 - Vertical Motion Comparisons

Interestingly a relatively comfortable ride is obtained from a hydrofoil with a fully-submerged foil system even when it is hullborne at very moderate speeds. This is because the foils and struts act as large dampers to the motion that would be imparted to the hull by large waves.

Sea State Degradation

Figure 49 shows operating data points for several submerged-foil hydrofoil ships in actual sea conditions. The data clearly show only a modest reduction in speed as wave heights increase. An operating envelope is drawn to represent hydrofoils designed to have a 50-knot speed capability in calm water.

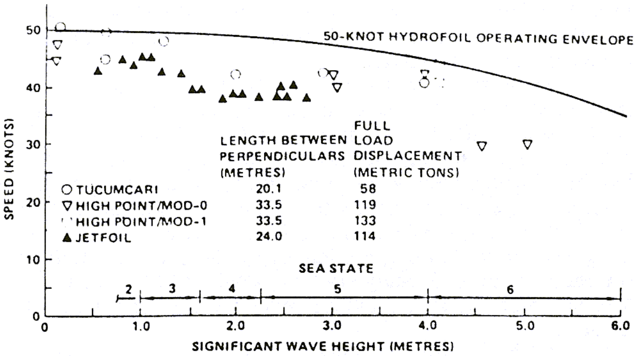


Figure 49 - Hydrofoil Speed Degradation

It is well known that ships slow down when the seas become rough. They do this for two reasons. First, it takes more power and hence more fuel is burned to travel a given distance, and second, the ride gets rough especially when the hull begins to slam as large waves impact the rapidly descending bow. This process of slowing down, for whatever reason, is known as Sea State Degradation. A hydrofoil, on the other hand, rides above the waves. The automatic control system maintains the hull and its occupants straight and level, so it does not have to slow down until it gets extremely rough and extremely large waves are encountered. Larger hydrofoils with fully-submerged foils and sufficiently long struts can delay the effect of waves to a much greater degree than smaller hydrofoils, particularly those with surface-piercing foils.

Maneuvering

Besides a significant speed advantage, hydrofoils are more maneuverable and provide a more comfortable turn than conventional ships. Foilborne turns are accomplished in a banked (coordinated) fashion. This causes the centrifugal force required in turns to be provided predominantly by the reliable lift capability of the submerged foils rather than by the unpredictable side forces from the struts.

A generic turn rate chart is shown in Figure 50 for coordinated turns. Here one can see that , for example, at a turn diameter of less than 500 meters can be made at 50 knots with a turn rate of 6 to 7 degrees per second.

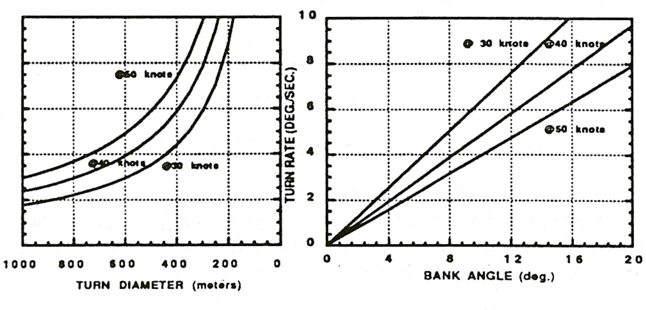


Figure 50 - Maneuvering Characteristics

Turn coordination enhances crew comfort during high-rate turns because the accelerations due to turning are felt primarily as slightly greater vertical forces rather than lateral forces. Lateral accelerations are close to zero. Therefore, hydrofoil ships have design turn rates of 6 to 10 degrees per second, and can maintain these rates in both calm and rough seas. This makes the hydrofoil ship a more difficult target for enemy missiles, guns, or torpedoes. The exceptional ride quality of the hydrofoil ship makes it a superior platform in which to mount surveillance equipment and weapons while maintaining crew comfort and proficiency. From a commercial aspect, passenger comfort is assure in most environments.

Hydrofoil Features

Weight Limitations

Like the aircraft designer, the hydrofoil designer must, at all times, be extremely conscious of weight. The hydrofoil type of craft is weight critical and every pound of weight saved in structure, machinery, or outfit means weight available for payload and fuel.

The structural engineer, in designing hydrofoils to conserve weight, uses aircraft techniques. Relative to conventional ships, hydrofoil craft are subject to very high loadings, as caused by high operating speeds. Likewise, lightweight, high strength materials are used. He also must contend with fatigue and problems of hydroelasiticity, including both divergence and flutter.

Hull Considerations

The development of a satisfactory hull form for hydrofoil application represents a significant challenge to the designer. The hull should perform well in the hullborne mode but also during takeoff and during foilborne operation where impacts with waves may be involved. In addition, the hull configuration of a hydrofoil ship must satisfy all of the requirements for strength, freeboard and intact and damaged stability for any other ship.

Relatively high power requirements for high-speed operation, in common with other high- performance systems, pay a high performance dividend for achieving a minimum weight structure. Therefore, hydrofoil ship hulls are generally constructed using high-grade aluminum alloys, 5000 series weldable alloy being typical. Structurally, the hull must have the strength to resist wave impact at high speed as well as distribute the concentrated load at the strut attachment points. Although hydrofoil hulls may appear quite conventional, the required compromises are more complex than for a monohull because of the many operating modes of the ship. An efficient hull form for a lower speed operation requires a narrow beam. However, a righting moment large enough to satisfy the stability criteria with the foils retracted generally dictates a wide beam. Cresting the tops of waves while foilborne points toward the use of a deep vee forward and high deadrise.

Trade-off studies must consider the factors mentioned above. Typical of current hydrofoils is a hull length to beam ratio of about 4:1; a sharp V forward; 20 degrees dead rise aft; hard chine planing surface hull shape; be constructed of 5456 H116 aluminum with all-welded frames and stringers using extruded skin panels with integral stiffeners. Hydrofoil hull weights, as shown in Figure 51, presently run between two and three pounds per cubic foot of enclosed volume.

Another major consideration in hydrofoil hull design is the requirement for good seakeeping characteristics in a heavy sea. If hydrofoil craft are to operate unrestricted in open ocean, they must be capable of surviving storm seas in the hullborne condition. Furthermore, in certain missions, it may be expected that a military hydrofoil ship will spend the greater 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, which is normal operation at sea, there is a significant

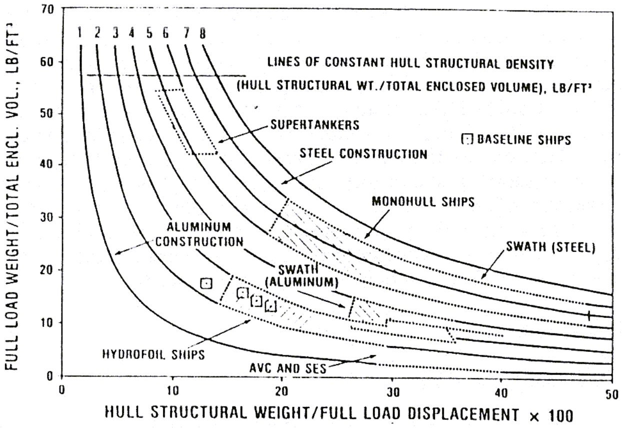


Figure 51 - Hull Weight Characteristics

reduction of craft motion, in both the roll and pitch modes which is normally not heavily damped. Thus the strut/foil system gives a hydrofoil craft the hullborne motion characteristics of conventional ships having much larger displacement.

Foil Systems

Foil variable lift is obtained by either trailing edge flaps or variable incidence of the entire foil as illustrated in Figure 14. Typical foil lift curves as a function of angle of attack and flap angle are shown in Figure 52. Variable incidence control in which required change in lift force is achieved by changing the angle of attack of the entire foil is represented by the $\partial=0$ curve. With flap control, change in lift force is obtained by changing the angle of the trailing-edge flap and, to a limited extent, the pitch angle of the ship. Of particular significance is the loss of lift capability which occurs when the upper surface is ventilated. A broached or ventilated foil cannot supply necessary control or stabilizing forces. Also, a broached foil does not rewet immediately upon reentering the water at high angles of attack.

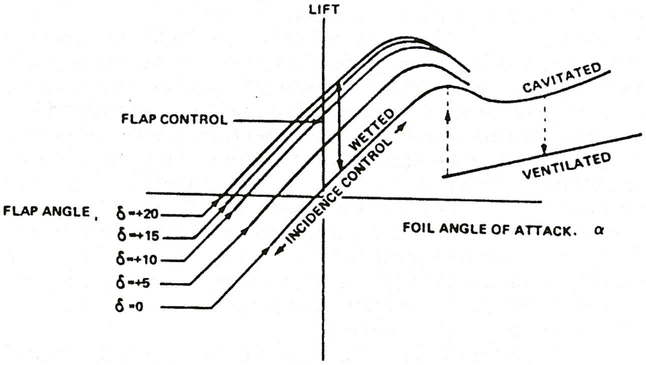


Figure 52 - Typical Foil Lift Curves

Foils with trailing-edge flap control have demonstrated superior recovery characteristics from a forward foil broach compared to variable incidence foils. To overcome this difficulty, variable incidence foils have successfully used broach recovery devices. Such devices sense an impending broach and preset the broaching foil to a low angle of attack. This affects lift recovery when the foil reenters the water. The longitudinal location of roll control is not particularly significant for operations in which the foils are always submerged and fully wetted. In these cases a roll-righting moment is generated for either canard or conventional configuration by differential control surface movement. However, in the case of a forward foil broach, the difference in response between canard and a split-foil conventional configuration can be dramatic. When the forward foil broaches on a canard configuration, little or no rolling moment results. The ship merely pitches down as the foil reenters the water and recovers lift.

A rolling moment will not normally be generated by broach of the forward foils of a conventional configuration if both foils broach simultaneously. However for split forward foil configurations, the more frequent occurrence is for one of the forward foils to broach. The off-center loss in lift results in a combined roll and downward pitch in the direction of the broached foil. Therefore the single forward foil of the canard configuration has been found to be the best configuration for recovery from a foil broach.

To be directionally stable without control augmentation, the lateral center of pressure of the underwater surfaces of the struts must be aft of the center of gravity. However, hydrofoil ships operating in rough water encounter large changes in water height. Hence, side force generation can be quite different between forward and aft struts. The movable forward strut (rudder) of a canard configuration, however, will provide increased controllability, particularly if the entire forward strut rotates as in the U.S. Navy HIGH POINT and PHM hydrofoils. The situation is similar during recovery from a forward foil broach .

As hydrofoils increase in size. the complexity of rotatable forward struts increases. Such struts must have bearings which can support the lift of the forward foil and still allow strut rotation. It is expected that very large hydrofoils will use a tandem configuration with either strut flaps or rotatable strut fairings for directional control.

A fundamental limitation on foil size is imposed by the so-called "square-cube" law, which impacts the growth potential of hydrofoil ships. The lift developed by the foils is proportional to their planform area (the square of a linear dimension), whereas the weight to be supported is proportional to a volume (the cube of a linear dimension). It follows that as size of the hydrofoil is increased, the foils tend to outgrow the hull. The aircraft problem is solved by increasing takeoff speed and wing loading as size is increased, but practical hydrofoil speeds are limited by cavitation. In the early period of hydrofoil development it was felt that an increase in the foil and strut weight fraction by direct application of the square-cube law would inherently limit hydrofoil size. More detailed design studies show that foil system weight fractions increase only slightly with displacement, Figure 53. The principal reasons why the weight fraction does not increase as might be expected is that required strut length varies with design sea state, not ship size, and larger foils are structurally more efficient.

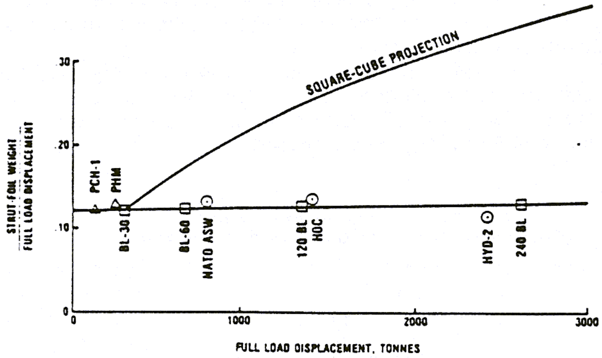


Figure 53 - Foil System Weight Fraction Trend

For hydrodynamic efficiency, it is desirable to use as high a foil aspect ratio (span/chord ratio) as possible. The PHM aft foil extends almost 10 feet on either side of the hull. Thus, a camel is normally used to hold the ship away from the pier for mooring. When no camel is available the ship must be moored across the end of a pier or the transom of a larger ship with the stern overhanging. PHMs have occasionally nested bow to stern. As ship size increases and foils grow relative to the hull and in actual dimension, practical considerations dictate efforts to limit the span. The trend will be to move toward tandem foil configurations to divide the weight more evenly between the forward and aft foils.

An example of a surface-piercing foil system is the Rodriquez "W" foil system shown schematically in Figure 54. The forward and aft foil system components are largely hollow weldments which have been manufactured from nickel-copper alloy steel. The welded assemblies are fixed to structural hard points at the hull using bolt-up attachments. The trailing edge flaps shown in Figure 17, which are installed on the RHS 200 foil systems, are not required for normal operation of the ship. Basically, the lift forces developed by a conventional surface-piercing hydrofoil system are functions of the submerged area of the foils and the square of ship speed. As ship speed is increased in the hullborne mode, increasing values of lift are generated by the essentially fully submerged foil system. Takeoff occurs at a speed where the lift forces are sufficient to support the weight of the ship. As the hull clears the water surface, lift-producing elements of the foil system are also exposed and an inherent trade-off between ship speed and remaining submerged foil area is initiated. Flying height is maintained without the use of height sensors, automatic control systems, or similar equipment. A surface-piercing foil system is inherently stable in all modes of foilborne operation, including calm and rough water conditions and turning maneuvers.

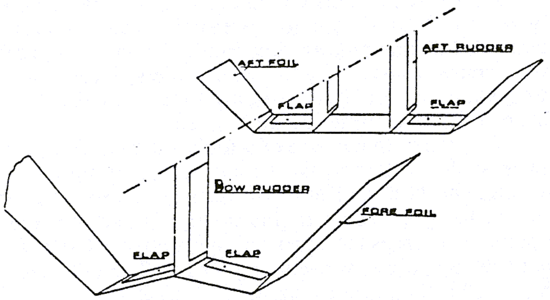


Figure 54 - Rodriquez "W" Foil

Many of the Soviet hydrofoils are equipped with the so-called Alexeyev shallow-draft submerged foil system developed by Dr. R.Y. Alexeyev in 1945. The system was specifically designed for operation on smooth, but open and shallow rivers and canals. The basic principle underlying Alexeyev's foil system is the immersion depth effect (or surface effect based on Wankel's earlier work, according to von Schertel) for stabilizing foil immersion in calm water by the use of small lift coefficients.

The Alexeyev system, shown in Figure 55 consists of two main horizontal foil surfaces, one forward and one aft, with little or no dihedral, each carrying about one half the weight of the craft. A submerged foil loses lift gradually as it approaches the water surface from a submergence of about one chord length. The effect prevents the submerged foil from rising completely to the surface. A planing sub-foil of small aspect ratio is used as a means of providing take-off assistance and preventing the hydrofoil from settling back to the displacement mode. The planing sub-foils are located in the vicinity of the forward struts arranged so that when they are touching the water surface, the main foils are submerged approximately to a depth of one chord.

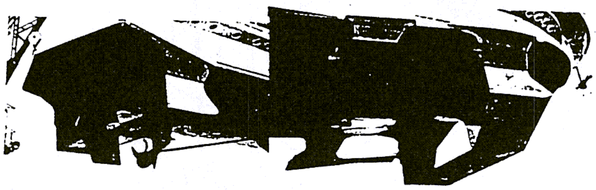


Figure 55 - Alexeyev Foil System

The Alexeyev system was first tested on a small launch powered by a 77 hp converted automobile engine. The Soviet hydrofoil RAKETA was the first production passenger ferry to utilize the system, and there were many such craft that followed. However, over the years, Soviet hydrofoils and their foils systems have been developed where their military craft in particular use fully-submerged foils aft and surface piercing foils forward which resemble those designs in the West.

Propulsion Systems

The propulsion system of a modern hydrofoil consists of three major components: the engine (or prime mover), the transmission system that transmits the power to the third element, namely the propulsor (or thrust producer).

Modern hydrofoil military ships and commercial passenger ferries have been made possible by the development of light-weight diesel engines and marinized gas turbine engines. Most of the European commercial ships using fixed surface-piercing foil systems have used lightweight diesel engines driving subcavitating propellers by means of an angled transmission system. This combination provides simplified construction, relative ease of maintenance, and low cost. However, the comparatively high specific weight (6-8 pounds per horsepower) of these diesel engines and higher overall drag have resulted in practical design speeds of these ships of about 35 to 40 knots.

An example of a diesel engine installation is shown in Figure 56. Note that in this case there is no separate propulsion system dedicated solely to either hullborne or foilborne operation. The diesel engines are used throughout the entire speed range of the hydrofoil. This is because such craft are usually designed as passenger ferries. Hence, they operate at high speed most of the time; low speeds being only necessary when maneuvering in and around the pier, around other boats or through narrow passages.

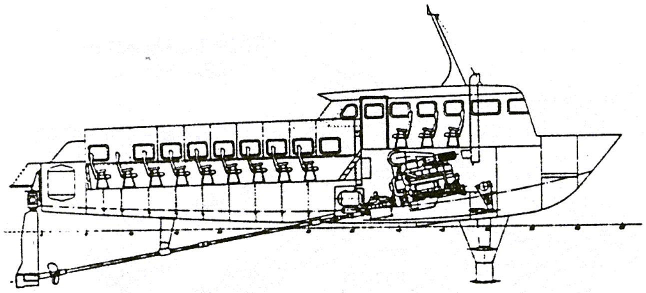


Figure 56 - Diesel Engine Installation

However, for hydrofoils where higher speeds are demanded, a gas turbine engine is used for foilborne operations and another, completely independent propulsion system is built into the ship for slow speed operations when on the hull. This may seem like a waste, or duplication, but the state of the art does not allow the hydrofoil designer to provide a gas turbine propulsion system that can handle both speed regimes efficiently.

Existing aircraft gas turbine engines slightly modified and coupled with specially designed free powered turbines are available in sizes with power ratings up to about 30,000 horsepower and specific weights of about 0.5 pounds per horsepower. The newer large engines employing blade cooling techniques have specific fuel consumption rates at their design power only somewhat higher than diesel engines. Gas turbine engines have been used in all major U.S. military and commercial hydrofoil ships permitting practical design speeds greater than 40 knots.

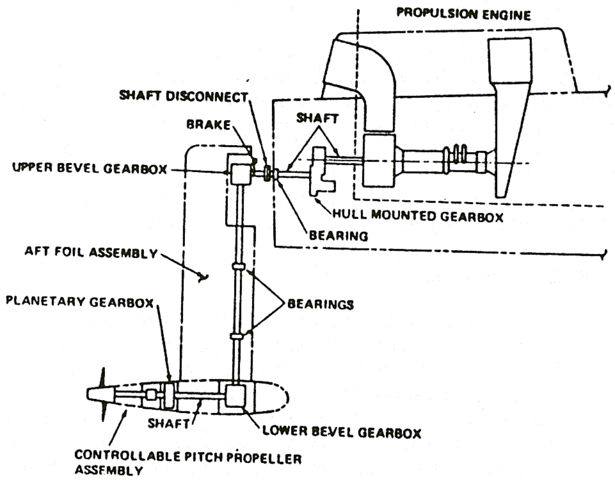


Figure 57 - FLAGSTAFF Propulsion System

An example of a foilborne gas turbine driven propulsion system is shown in the illustration of the FLAGSTAFF foilborne propeller propulsion system as seen in Figure 57. Here the gas turbine is mounted in the aft section of the hull in such a way that the air intake is located forward. The exhaust stack is positioned further behind in the hull and the exit is directed aft so as not to contaminate the intake air or raise its temperature. A gas turbine requires much more air than a diesel engine of comparable power. Adequate intake ducting for the air is required to keep flow rates below certain limits. Likewise the exhaust air duct must be large enough so as not to produce undesirable back pressure on the engine which can adversely affect its operation. Although not shown in the FLAGSTAFF propulsion system installation, there are two small waterjets driven by small diesel engines to provide thrust for hullborne operations.

A hydrofoil with fully-submerged foils and long struts poses a challenging problem for the mechanical engineer to transfer power from the engine located in the hull to one or more propellers located at or below the foils. A surface-piercing foil with relatively short struts uses an angled shaft. However, for the former case, a Z-drive is depended upon to transmit the power. This means that a series of gearboxes and shafts are required to turn all the corners to transfer power from the hull level to the lower level at the bottom of the strut or struts. Hence, the use of the term "Z-drive".

Propellers are the most efficient propulsion device available for operating over the subcavitating speed range of current hydrofoil ships. The power transmission systems required when using fully submerged foil systems consist of right angle bevel gears, flexible shafts and possibly a speed reduction gearbox in the propeller transmission pod. Examples of transmission/propeller Z-drive systems are given in Figures 57 and 58 from FLAGSTAFF, PLAINVIEW and HIGH POINT. Here one can trace the transmission of power from the gas turbine engines through the various gearboxes via shafts to their final destination, the propellers at the bottom of the major struts of the foil system.

Problems encountered with gear transmission systems in early hydrofoil ships led to interest in waterjet propulsion systems. While not entirely eliminating the need for gearboxes, these systems consist of underwater inlets, water ducts with turning vanes in the struts, a pump located in the machinery space, and an above-water exhaust nozzle.

The water, in the case of a foilborne hydrofoil, has to be taken in at the bottom of the aft struts, carried up through the struts into the hull, and into the waterjet pump. The latter is driven by the gas turbine engine through a gearbox and shaft. The pump discharges the water through a nozzle, located near or on the transom, thereby producing thrust. The example shown in Figure 59 is the system from the TUCUMCARI.

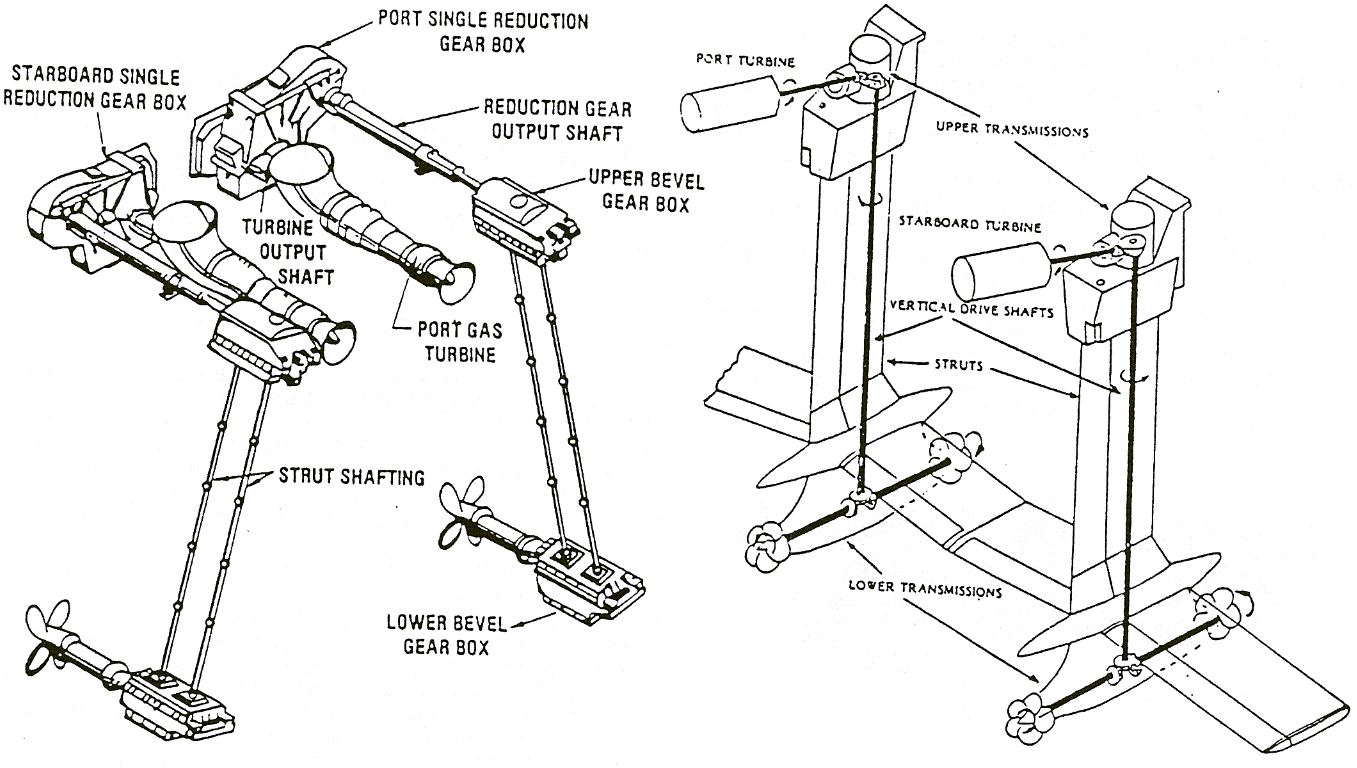


Figure 58 - PLAINVIEW and HIGH POINT Transmission Systems

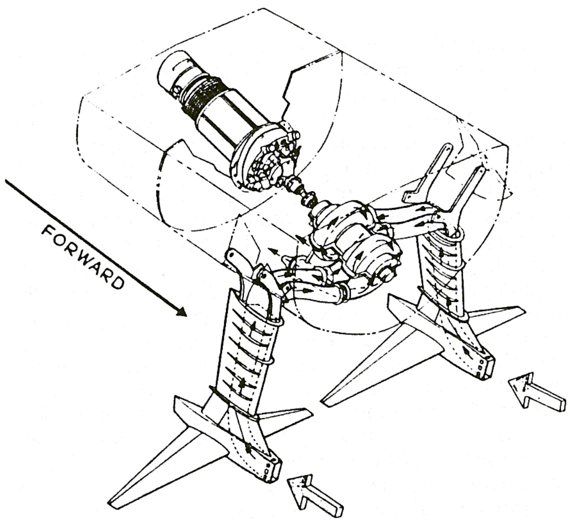


Figure 59 - TUCUMCARI Propulsion System

The U.S. Navy's PHM propulsion system also utilizes a waterjet which is shown on Figure 60. The price paid to achieve these less complex waterjet systems is a decrease in propulsive efficiency of about 20% at 45-50 knots and even a greater decrease at takeoff speeds along with the additional weight of water carried in the propulsion system.

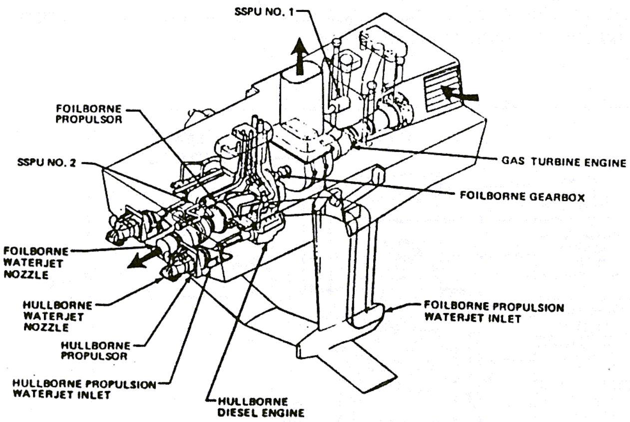


Figure 60 - PHM Propulsion System

Obviously, the waterjet and propeller systems each have their pros and cons which the hydrofoil designer must consider during the feasibility and preliminary design of a given hydrofoil. Much has been learned from the various hydrofoils and their particular propulsion systems built to date. An illustration that delineates the two basic systems is shown in Figure 61 in terms of several hydrofoil performance parameters. Note the large difference between "propeller" and "waterjet" for both propulsive coefficient and shaft horsepower per ton. The former parameter is a measure of the efficiency of the propulsion system, or how well the system transmits power from the engine to the water. The second parameter, engine shaft horsepower per ton of ship weight, is a result of combining the efficiency values and the lift-to-drag ratio characteristics of the foil system.

A relatively new development has been undertaken for the Rodriquez MEC-1 hydrofoil, namely a Hydromarine hydrostatic transmission system. The Power Shaft HS-5000 consists of a pod mounted tractor propeller, a variable displacement hydraulic pump and hoses running between the prime mover and the pod. At present the power range of the HS-5000 is 300 to 1,400 kW per unit. Figure 62 shows a schematic arrangement of the system in the MEC-1.

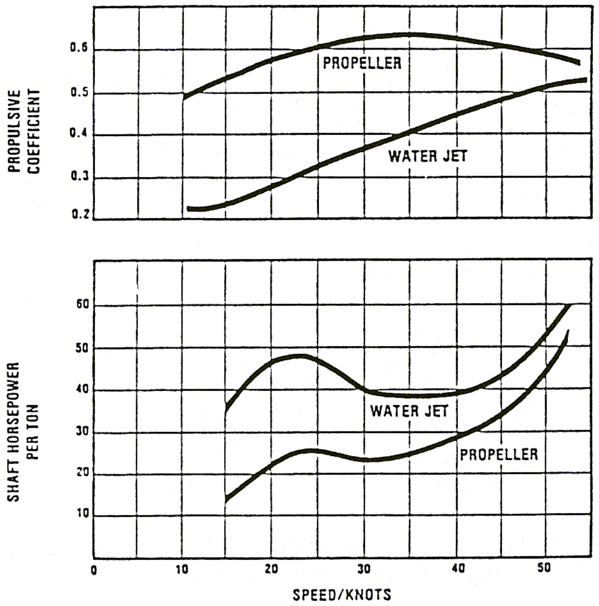


Figure 61 - Comparison of Propeller and Waterjet Systems

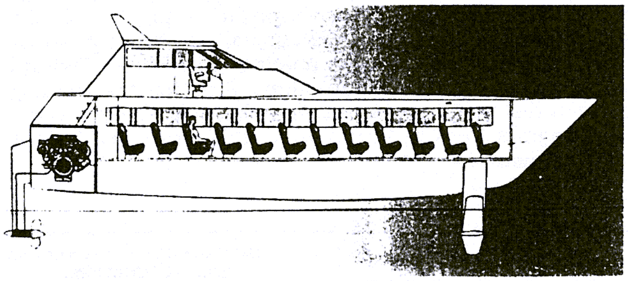


Figure 62 - MEC-1 With Hydraulic Transmission System.

Automatic Control System

As noted earlier, surface-piercing hydrofoil configurations are self-stabilizing in both pitch and roll and thus do not require an automatic control system. However, to reduce the inherent reaction to rough seas, a number of such hydrofoils have added trailing-edge flaps to the surface-piercing foils and employ autopilots for ride comfort improvement.

It is particularly difficult, if not impossible, to manually control a high-speed hydrofoil craft with a fully-submerged foil system, particularly operating in rough water. Such craft therefore depend on an automatic control system (ACS) that constantly adjusts foil angle of attack, either through changes in foil incidence or flap angle. These adjustments are made to both port and starboard, as well as fore and aft foils, to maintain trim and keep the hull at a given height above the mean water surface in the presence of disturbances. In order to achieve as high a lift-to-drag ratio (or minimum drag for a given amount of lift) as possible in the cruise condition, the foils are designed to operate with relatively small mean incidence or flap angles. This then provides adequate reserve to generate the required control forces. This is necessary because of the changes in foil angle of attack resulting from the orbital velocities of waves which, if not compensated for, could produce significant ship motions.

These wave induced excitations must be compensated for by the control system if the hydrofoil is to fly straight and level and remain foilborne in large waves without excessive cresting of the hull or broaching of the foils. The latter refers to a condition when a foil breaks through the water surface, loses its lift, and can cause the craft to go hullborne with a loss of speed. The hydrofoil has to then reaccelerate and become foilborne again.

There are two modes in which a hydrofoil control system operates, namely, platforming and contouring modes. As the name implies, in the former mode the craft flies at a given height above the mean water surface, as illustrated in Figure 63, and is controlled automatically so that there is minimum ship motion. The limit on this mode is a function of wave height and foil system strut length. When wave height exceeds a value where the ship can no longer "platform", the operator resorts to the contouring mode in which the hydrofoil flies approximately parallel to the smoothed contour of the sea surface or essentially follows the wave contour.

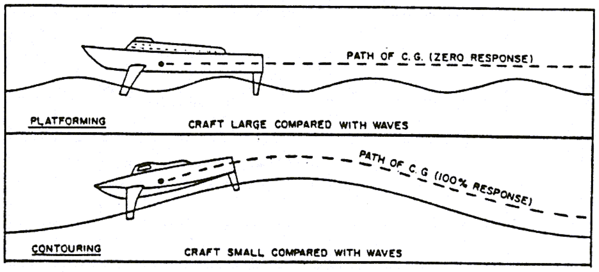


Figure 63 - Hydrofoil Foilborne Modes

In the United States Navy, full automatic control of submerged foils has been deemed necessary to attain the seaway performance desired for ocean-going hydrofoil ships. Typically, control is accomplished by positioning trailing-edge flaps on the forward and after foils and by rotating the swiveled forward strut (rudder), or by moving the entire foil surface and by using the power driven aft strut as a rudder. A typical control system block diagram for a hydrofoil with fully-submerged foils is shown in Figure 64.

The control surfaces are positioned by means of conventional electrohydraulic servos. The control system motion sensors consist of: 1) a vertical gyro which measures craft pitch and roll angular motion, 2) a rate gyro which measures craft yaw rate, 3) three vertical accelerometers, one accelerometer being located approximately on top of each strut (the two aft accelerations work differentially to provide roll angular acceleration feedback, and they work in unison to provide pitch and heave acceleration feedback), and 4) a height sensor which measures the height of the bow above the water surface. The manual inputs consist of a foil depth command, which the helmsman uses to select any desired foil depth (or flying height), and the helm, which introduces the craft turning commands.

The ACS provides continuous control during takeoff, landing, and all foilborne operations. The pitch, roll, and height feedback loops provide automatic stabilization of the craft. The craft is automatically trimmed in pitch by the pitch feedback, and roll trim is accomplished by helm inputs. To steer the ship, the helmsman simply turns the helm, and the ACS automatically maintains a coordinated turn, with turn rate being proportional to helm deflection.

An improvement in one of the radar height sensor has been experimented with by Boeing and shows promise. This is called a Forward Looking Radar Height Sensor. It is a device that will determine wave height well ahead of the hydrofoil and in sufficient time, switch automatically from one mode (platform or contour) to the other to minimize not only ship motion, but loads imposed on the foil, hydraulic systems, and hull.

All of the complexities of the ACS have resulted in a hydrofoil with superior seakeeping and ability to provide an extremely comfortable ride for the personnel aboard. With modern electronics, these systems can be built in compact packages and with high reliability.

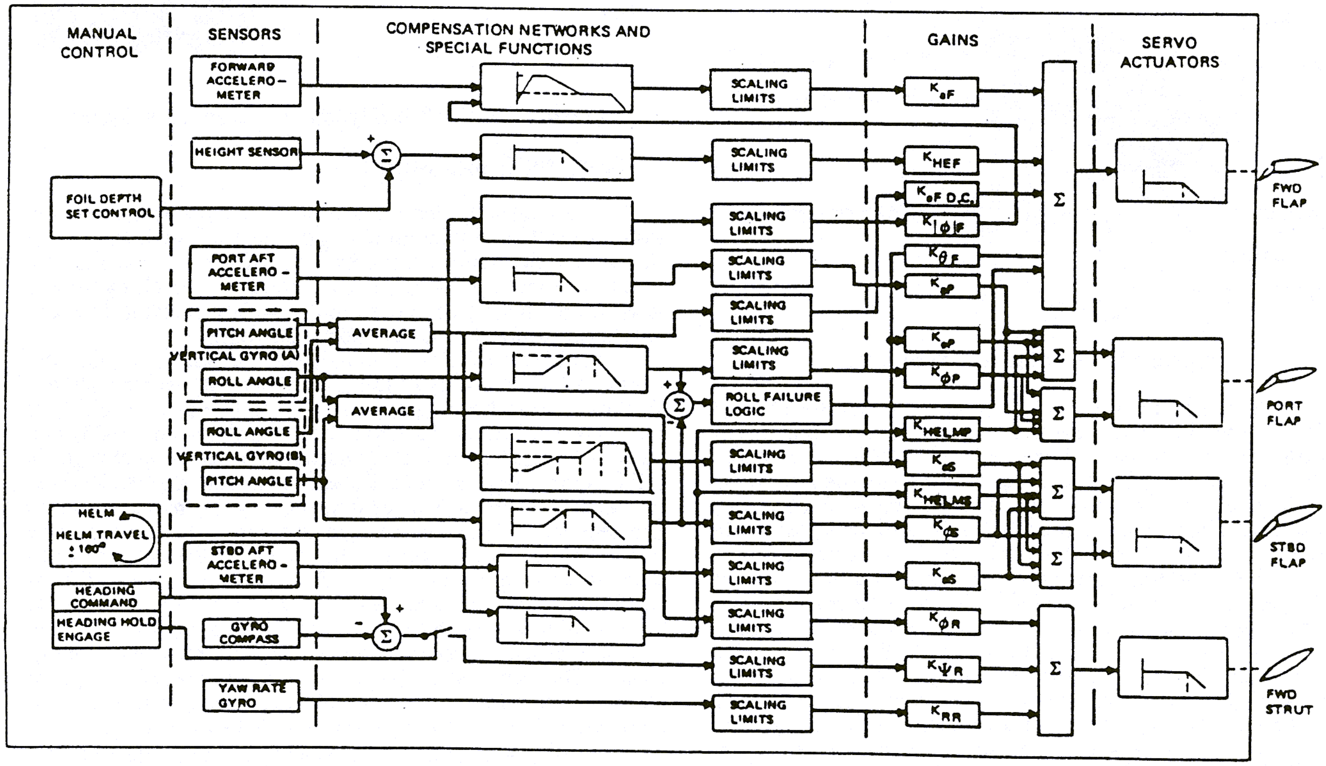


Figure 64 - Typical Hydrofoil Control System

Hydrofoil Design

Basic Theory and Design Tools

Commercial hydrofoil manufacturers each have their own design methods based on their experience which may have involved a lot of "cut and try" attempts. The details of these methods are closely guarded, and hence not usually available to everyone. There has been a limited amount of recently published material on this subject, primarily because it is somewhat complex, and there is not a great deal of motivation to do so. Crewe has provided the basic theory of the hydrofoil. Also, a publication by Gibbs and Cox for the Office of Naval Research also provides, in two volumes, the host of relationships that the designer requires to even complete a preliminary design. The U.S. Navy developed a series of documents on Hydrofoil Design Criteria including Substantiation material which contains a wealth of hydrofoil characteristics and design data.

The U.S. Navy has developed an elaborate design tool which is very useful in exploring hydrofoil designs. The computer program allows the user to examine a variety of designs to meet certain requirements of speed, range, and payload relatively quickly, and determine the sensitivity of the overall design to certain physical parameter changes. This capability grew out of a computer program called HANDE (Hydrofoil ANalysis and DEsign) developed by Boeing Marine Systems under U.S. Navy contract. This tool is now included as the Hydrofoil set of manuals under the Navy Advanced Surface Ship Evaluation Tool (ASSET).

King and Devine explain that the use of the "HANDE" engineering system closely parallels the classical process of ship design. The design begins with a set of mission requirements for the ship. For example, this includes such parameters as speed, range, mission endurance, payload, and crew size. Existing design data in the form of a "model parameter list" are employed in an iterative sequence to derive the hydrofoil design in a fashion that it frequently described as a "design spiral". In this manner the initial design starts on the outside of the spiral, is modified as the various elements of the design impact on each other, and closes at the center of the spiral on a design that meets all of the requirements.

It is essential to realize that, although the computerized design tool automates many of the more arduous tasks in designing a hydrofoil, the critical engineering decisions that heavily impact on the design are still left to the individual designer. For instance, HANDE does not decide whether to employ waterjet or propeller propulsion, and if a propeller is selected by the designer, what kind of propeller to use. Such decisions are in the hands of the hydrofoil designer. However, he has the opportunity to quickly vary the design by incorporating waterjets in one design, and propeller propulsion in another. When both are computed to the same requirements, he can then make a comparison to determine the superior approach.

CONCLUDING REMARKS

Hydrofoil technology, like ACV and SES technology, is considered to be well understood in the U.S. Fifteen years of operational experience with the PHM-1 Class hydrofoils has demonstrated that the concept can be used for a military mission with success. However, further development of hydrofoils has essentially been stopped because the Navy has not placed sufficient priority on the patrol craft mission. Although the Navy has performed numerous studies of hydrofoils up to 2400 tons covering long range, open-ocean ASW missions, specific Operational Requirements were never forthcoming. Like the SES, the hydrofoil faces the problem of lack of high priority Navy mission in spite of its superior motion characteristics and ability to maintain high speed in heavy seas relative to the conventional monohull. The hydrofoil has been perceived to be appropriate for the patrol craft size, but not in a larger size. This, of course, is no longer so, since the technology exists for larger hydrofoils or a promising alternative - namely, the hybrid hydrofoil concept. The latter has been studied over a broad size range. Hybrid hydrofoil technology has been adopted by the Japanese (Kawasaki) for the design of a 3,000 to 4,000 ton Techno-Superliner.

The limited range, unique shore-based infrastructure, relatively high acquisition cost, and perceived high ownership costs of the PHM have been principally responsible for the lack of interest in future hydrofoils in the Navy. It is unfortunate that this perception still exists since the technical community has proposed solutions to triple the range of the PHM, decrease acquisition costs (on a per ton basis) of follow-on ships, and reduce ownership cost by improving reliability and maintainability.

Commercial interest in hydrofoils has also waned in the U.S., although it was never at anywhere near that of the Europeans (principally Italy and the Soviet Union). Boeing, because of its very high-tech JETFOIL, and associated high production costs, was not able to compete in the world-wide market. They have ceased domestic production, and licensed production of JETFOIL to Kawasaki Heavy Industries who has established a promising market in the "Pacific Rim". Except for Westfoil International, the U.S. industrial base experienced in hydrofoil construction has eroded, at least in the construction of hydrofoils with fully-submerged foils. However, it has been reported that Kawasaki is seeking a U.S. builder for JETFOIL so as to be able to market the craft in this country. Whether successful hydrofoil operation outside the U.S., or the interest in foil lift as an adjunct to other hull forms (e.g., monohull, catamaran, SWATH and SES) will reinvigorate U.S. industry, remains to be seen.

SUMMARY

From the foregoing, it can be seen that the basic concepts of hydrofoil-borne flight were developed from about 1905-1915, with the interesting footnote that these efforts were motivated primarily from an interest in helping seaplanes take off and land rather than an interest in marine applications. The work of von Schertel and his colleagues in Germany just prior to and during World War II converted what had been an interesting scientific phenomenon into a potential commercial and military reality, by concentrating on a basic configuration of surface-piercing foils.

In the immediate post war period, von Schertel, in concert with Sachsenberg and Rodriguez, converted the commercial potential into reality. In the same time period, the Soviet Union, drawing heavily upon the German results, also developed effective commercial applications, but, in addition, developed highly capable military applications. Many of the Soviet applications used an adaptation to surface-piercing foils that incorporated the additional use of submerged foils operating close to the water surface .

The successful use of surface-piercing foil configurations in these initial commercial and military applications was primarily due to the fact that the craft were operated in locations where the water surface was normally quite calm, such as on lakes and rivers. Even coastal operations could be carried out except in poor weather.

In the United States, on the other hand, the immediate post-war period saw a relatively large amount of basic research carried out, but no commercial development. The success of the fully submerged foil systems with automatic controls, demonstrated on SEA LEGS, caused the focus of U.S. development to center on that type of system. the additional expense of the required height-sensing systems, flaps on the foils and automatic control systems could only be justified in military applications, where seagoing performance was an absolute requirement. research into very high speed performance, involving supercavitating foils and propellers, was carried out, only to prove to be very difficult. The great success of the PGH-1 and PGH-2 led not only to the NATO PHM programs but also to the Italian NIBBIO and to the Israeli SHIMRIT classes.

Finally, in more recent times, it appears that the commercial operators in all countries are tending more and more to the submerged foil technology. The reasons for this appear obvious. The notably improved ride qualities and the ability to operate foilborne (at high speed) in much more severe sea conditions are clearly great advantages for passenger service operators. The greatly reduced cost of electronic systems, at least relatively, appears to have brought the additional high-tech system capabilities within economic feasibility.

At the present time there is also great interest in the use of hydrofoils to improve the ride qualities of multi-hull forms, without necessarily raising the hulls clear of the water surface. It will be interesting to see how the cost equations work out as these potential competitors to pure hydrofoils are put into commercial service. It may well be that such hybrids will be competitive for many relatively smooth water applications, but in the opinion of the authors, the true hydrofoil will provide superior performance where rough water is encountered .

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